REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT DATE	3. DATES COVERED (From - To)
09-12-2003	Bi-annual Performance/Technical Report	6/1/2003 – 11/30/2003

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Energy Efficient Wireless Sensor Networks Using Fuzzy Logic	5b. GRANT NUMBER N00014 – 03 –1 –0466
	5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)	5d. PROJECT NUMBER
Liang, Qilian	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
University of Texas at Arlington Office of Sponsored Projects PO Box 19145 Arlington, TX 76019	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
Office of Naval Research 800 North Quincy Street Arlington, VA 22217-5660	ONR
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT

Approved for Public Release; Distribution is Unlimited.

20031217 209

13. SUPPLEMENTARY NOTES

14. ABSTRACT

During the period 6/1/2003 -- 11/30/2003, we have made lots of progress on energy efficiency of wireless sensor networks. We investigated the optimal number of clusters for a given number of sensors. Based on this theoretical result, we proposed a Fuzzy Energy Aware Topology Updated with REconfiguration for sensor-networks (FEATURES) scheme. This scheme provides a methodology on how to partition a sensor network to the desired number of clusters using fuzzy c-means, how to elect a clusterhead using fuzzy logic system via combining different descriptors of a sensor: distance of a node to the cluster centroid, its remaining battery capacity, and its degree of mobility. We also proposed an Access-Based Low Energy Hierarchy (ABLEH) to clustering protocols more adaptive to the dynamic nature of sensor networks. Besides, we studied energy efficient protocol design for large-scale wireless sensor network. Four papers were produced during these six months, and are attached to this report.

15. SUBJECT TERMS

Wireless Sensor Network, Energy Efficiency, Fuzzy Logic

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			QILIAN LIANG
U	U	U	UU	29	19b. TELEPONE NUMBER (Include area code) 817-272-1339

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI-Std Z39-18

BEST AVAILABLE COPY

Performance/Technical Report for N00014-03-1-0466
Energy Efficient Wireless Sensor Networks Using Fuzzy Logic

Qilian Liang

Department of Electrical Engineering

University of Texas at Arlington

Arlington, TX 76019-0016 USA

Phone: 817-272-1339, Fax: 817-272-2253

E-mail: liang@uta.edu

Abstract

During the period of 6/1/2003 – 11/30/2003, we have made lots of progress on energy efficiency of wireless sensor networks. We investigated the optimal number of clusters for a given number of sensors. Based on this theoretical result, we proposed a Fuzzy Energy Aware Topology Updated with REconfiguration for Sensor-networks (FEATURES) scheme. This scheme provides a methodology on how to partition a sensor network to the desired number of clusters using fuzzy c-means, how to select a clusterhead using fuzzy logic system via combining different descriptors of a sensor: distance of a node to the cluster centroid, its remaining battery capacity, and and its degree of mobility. We also proposed an Access-Based Low Energy Hierarchy (ABLEH) to make clustering protocols more adaptive to the dynamic nature of sensor networks. Besides, we studied energy efficient protocol design for large scale wireless sensor network. Four papers were produced during these six months, and are attached to this report.

1 Determine the Optimal Number of Clusters

Suppose the total number of nodes is N, what's the optimal number of clusters K? One special case is $K = N$, which means every node can directly communicate to the gateway; another special case is $K = 1$, which means all sensors are in one cluster. Both cases are not efficient for energy efficiency purpose. We have systematically investigated this theoretical topic for wireless sensor networks [2], which is significant for the initialization of energy efficient self-organizing sensor networks. We set up a cost function based on the energy consumption of the whole sensor network, and determined the optimal number of clusters via optimizing this cost function. This cost function have combined many parameters and descriptors, e.g., the geography information of every node, path loss model, distance to the gateway (or base-station), and data fusion etc. We have found a closed form formula

for K [2],

$$K = \sqrt{\frac{N\epsilon_{mp}}{\pi\epsilon_{fs}}} \frac{d_{toBS}^2}{R} \tag{1}$$

where N is the total number of sensors, d_{toBS} is the average distance between the sensor network and base station (or gateway), R is the radius of sensor network, ϵ_{mp} and ϵ_{fs} are some constant coefficients related with the energy amplifier during transmission.

2 FEATURES: Fuzzy Energy Aware Topology Updated with RE-configuration for Sensor-networks

Based on the optimal number of clusters for energy efficient sensor network, we have investigated how to partition the N nodes to K clusters [1]. We have applied fuzzy c-means (FCM), an un-supervised clustering method, to the clustering of self-organized wireless sensor networks. FCM clustering is a data clustering technique where each data point belongs to a cluster to a degree specified by a membership grade. We have tried to minimize the following function

$$J(\mathbf{U}, \mathbf{v}) = \sum_{i=1}^{K} \sum_{j=1}^{N} (u_{ij})^2 (d_{ij})^p \tag{2}$$

where d_{ij} is the is the Euclidean distance between one node ($\mathbf{x}_j$) and its cluster center ($\mathbf{v}_i$), and u_{ij} is the membership grade of sensor node j belonging to cluster i ($i = 1, 2, \cdots, K$) and $\sum_{i=1}^{K} u_{ij} = 1$. The minimal $J(\mathbf{U}, \mathbf{v})$ is obtained based on an iterative method by adaptively updating u_{ij}. We can determine which cluster each sensor node belongs to based on the maximum membership from u_{ij} ($i = 1, 2, \cdots, K$).

A clusterhead has to be selected following the formation of a cluster. Selecting an appropriate clusterhead can save energy for the whole wireless sensor network. Generally, clusterhead election for mobile ad hoc (sensor) network is based on the distance to the centroid of a cluster, and the closest one is elected as the clusterhead; or pick a node with the maximum battery capacity as the clusterhead. we proposed a clusterhead election scheme using fuzzy logic system (FLS) [4]. Three descriptors were used: distance of a node to the cluster centroid, its remaining battery capacity, and and its degree of mobility. The linguistic knowledge of clusterhead election based on these three descriptors was obtained from a group of network experts. 27 FLS rules were set up based on the linguistic knowledge. The output of the FLS provided a clusterhead possibility, and node with the highest possibility was elected as the clusterhead.

For mobile ad hoc wireless networks, the position of each sensor changes over time, the protocol must be able to dynamically update its links in order to maintain strong connectivity. A network protocol that achieve this is said to be "self-reconfiguring". Our fuzzy energy aware topology can dynamically and recursively update the number of clusters, the partition of clusters, and clusterheads [1]. This scheme works because our approaches are iterative optimization method,

2

and the existing topology is the initial values for the next iteration. We further modified this mobility management scheme with hysteresis to overcome the *ping-pong* effect [1].

3   An Access-Based Low Energy Hierarchy for Sensor Networks

We proposed the Access-Based Low-Energy Hierarchy (ABLEH) [2]. It is especially designed for energy efficiency and higher tolerance to topology changes. And for higher tolerance to interference, low detectability and multiple access communication by a large population of relatively uncoordinated users, Direct Sequence Spread Spectrum is utilized in ABLEH. Some Spread Spectrum codes may be set aside as public channels, and each cluster has its own Spread Spectrum code so that the interference between clusters is minimized. For intracluster communications, TDMA is used with Adaptive Channel Assignment (ACA). Simulation results show that about 50% reduction can be achieved in energy dissipation and effective system lifetime are extended tremendously compared with LEACH.

4   Energy Efficient Protocol Design for Large Scale Wireless Sensor Network

In order to facilitate the management and routing of large scale wireless sensor networks, many algorithms have been proposed to partition mobile sensor nodes into clusters. In [3], we developed an Access-Based Energy Efficient (ABEE) clustering protocol, whose clustering algorithm is based on the outcome of the multiple access to the public channel. ABEE retains the advantage of access-based scheme such as self-organization, flexibility and stability. Also by considering the energy dissipation during the compression and transmission of the collected data, ABEE can provide uniformly distributed and energy efficient infrastructure for the upper lever protocols. In [3], We also proposed to use coverage area to judge the robustness of the network as well as the number of active nodes. Simulations were used to compare ABEE with the exclusively access-based clustering protocol in terms of rationality of the cluster structure, system lifetime and the coverage area. Our result shows that the ABEE can partition the large scale of nodes more rationally, efficaciously improve the system lifetime and the coverage area of the whole network.

References

[1] Q. Liang, "FEATURES: Fuzzy Energy Aware Topology Updated with REconfiguration for Sensor-networks," submitted to *IEEE Int'l Conference on Communications (ICC)*, June 2004, Paris, France.

[2] L. Zhao, Q. Liang, "An access-based low-energy hierarchy for sensor networks," submitted to *IEEE Int'l Conference on Communications (ICC)*, June 2004, Paris, France.

[3] X. Hong, Q. Liang, "An access-based energy efficient clustering protocol for large scale wireless sensor network," submitted to *IEEE Wireless Communications and Networking Conference (WCNC)*, Atlanta, GA, March 2004.

[4] Q. Liang, "Clusterhead election for mobile ad hoc wireless network," *IEEE Int'l Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sept 2003, Beijing, China.

FEATURES: Fuzzy Energy Aware Topology Updated with REconfiguration for Sensor-networks

Qilian Liang
Department of Electrical Engineering
University of Texas at Arlington
Arlington, TX 76019-0016 USA
E-mail: liang@uta.edu

Abstract— **In this paper, we propose a Fuzzy Energy Aware Topology Updated with REconfiguration for Sensor-networks (FEATURES). The sensor network is self-organized to clusters using a fuzzy clustering method for energy saving purpose. The clusterhead of each cluster is elected using a fuzzy logic system to maximize the network life. This topology is updated with reconfiguration to manage the mobility in mobile sensor networks since the the position of each sensor changes over time. We further modify this mobility management scheme with hysteresis to overcome the *ping-pong* effect. Simulation results show that our scheme performs much better than the Low-Energy Adaptive Clustering Hierarchy (LEACH) algorithm.**

I. INTRODUCTION

The wireless sensor nodes in sensor networks are networked together in an ad hoc fashion, which involves peer-to-peer communication in a network with a dynamically changing topology. They do not rely on a preexisting fixed infrastructure, such as a wireline backbone network or a base station. They are self-organizing entities that are deployed on demand in support of various events including collaborative computing, multimedia classroom, disaster relief, search and rescue, and interactive mission planning. Scalability and energy-efficiency concerns suggest a hierarchical organization of ad hoc networks (AHN) or sensor networks with the lowest level in the hierarchy being a cluster. As argued in [7] [5] [4] [12], in addition to helping with scalability and robustness, aggregating nodes into clusters has additional benefits:
1. conserving battery power;
2. promoting spatial code reuse and frequency reuse;
3. simplifying the topology, e.g., when a mobile node changes its location, it is sufficient for only the nodes in attended clusters to update their topology information;
4. reducing the generation and propagation of routing information; and,
5. concealing the details of global network topology from individual nodes.
Thus, it is important to design an optimal topology for self-organizing wireless sensor network to maximally extend the above benefits. Of these, conserving battery power is the most significant because battery life is not expected to increase significantly in the coming years and sensor networks are typically established in mission critical environments.

Singh et al [17] proposed power-aware routing and discussed different metrics in power-aware routing; Li et al [6] extended their work and proposed an online power aware routing in wireless ad-hoc networks. Recently, Block and Baum [2] proposed an energy-efficient routing protocol for wireless sensor networks with battery level uncertainty. A new topology management scheme, called STEM (Sparse Topology and Energy Management) was proposed in [16] for sensor networks, which can wake up nodes from a deep sleep state without the need for an ultra low-power radio. In [8], a data gathering algorithms in sensor networks using energy metrics, called PEGASIS (Power-Efficient GAthering in Sensor Information Systems), was proposed. In PEGASIS, each node communicates only with a close neighbor and take turns transmitting to the base station, thus reducing the amount of energy spent per round. In PEGASIS, the remaining battery capacity is assumed to have known. In sensor networks, lots of parameters can be uncertain, e.g., the remaining battery capacity, neighbor sensor locations, etc. In [3], a Low-Energy Adaptive Clustering Hierarchy (LEACH) scheme was proposed in [3]. In this paper, We apply fuzzy logic to energy efficient wireless sensor networks because fuzzy logic can handle the linguistic or numerical uncertainties in a natural way. In additions, for mobile sensor networks, the position of each sensor changes over time, the protocol must be able to dynamically update its links in order to maintain strong connectivity. A network protocol that achieves this is said to be "self-reconfiguring" [14]. In this paper, we propose a Fuzzy Energy Aware Topology Updated with REconfiguration for Sensor-networks (FEATURES).

The rest of the paper is organized as follows. In Section II, we propose a fuzzy energy aware topology for sensor networks. In Section III, we make this topology periodically updated with reconfiguration for mobile sensor networks, and this scheme is modified with hysteresis to overcome the *ping-pong* effect. In Section IV,

we compare our algorithm against the LEACH algorithm. Conclusions are presented in Section V.

II. FUZZY ENERGY AWARE TOPOLOGY FOR SENSOR NETWORKS

A. Energy Consumption Model and Cost Function

Three models are often used for energy consumption in the wireless transmission: path loss, large-scale variations, and small-scale variations [13]. Similar to [14], we concentrate only on path loss that has distance dependence which is well modeled by $1/d^p$, where d denotes the distance between the transmitter and receiver antennas, and the exponent p is determined by the field measurements for the particular system at hand [13], for example, $p = 2$ for free space, $p = 1.6 - 1.8$ for in building line-of-sight, and $p = 4 - 6$ for obstructed in building. Suppose there are c clusters in the wireless sensor network, and m_i nodes in the ith cluster, we use the following cost function to minimize the power consumption

$$J \triangleq \sum_{i=1}^{c} \sum_{k=1}^{m_i} (d_{ik})^p \qquad (1)$$

where p (path-loss exponent) is a constant for a fixed environment, and

$$d_{ik} = ||\mathbf{x}_k - \mathbf{v}_i|| \qquad (2)$$

where $|| \cdot ||$ is the Euclidean distance between one node ($\mathbf{x}_k$) and its cluster center ($\mathbf{v}_i$), where $\mathbf{x}_k$ and $\mathbf{v}_i$ can be 2-D or 3-D geography information. We partition the network to clusters via minimizing the total energy consumption using an unsupervised clustering – Fuzzy c-Means (FCM).

B. Network Partition Using an Unsupervised Clustering – Fuzzy c-Means

FCM clustering is a data clustering technique where each data point belongs to a cluster to a degree specified by a membership grade. This technique was originally introduced by Bezdek [1] as an improvement on earlier clustering methods. Here we apply FCM clustering to sensor network partition. Our objective is to partition n nodes to c clusters which will consume minimum power.

Definition 1 (Fuzzy c-Partition for Sensor Networks) Let $\mathbf{X} = x_1, x_2, \cdots, x_n$ be n nodes, $\mathbf{V}_{cn}$ be the set of real $c \times n$ matrices, where $2 \leq c < n$. The *Fuzzy c-partition space* for $\mathbf{X}$ is the set

$$M_{fc} = U \in V_{cn} | u_{ik} \in [0, 1] \ \forall i, k; \qquad (3)$$

where

$$\sum_{i=1}^{c} u_{ik} = 1 \ \forall k$$

and

$$0 < \sum_{k=1}^{n} u_{ik} < n \ \forall i$$

The row i of matrix $U \in M_{fc}$ contains values of the ith membership function, u_i, in the fuzzy c-partition U of $\mathbf{X}$.

Definition 2 (Fuzzy c-Means Functionals) We modify (1) to

$$J(\mathbf{U}, \mathbf{v}) = \sum_{i=1}^{c} \sum_{k=1}^{n} (u_{ik})^2 (d_{ik})^p \qquad (4)$$

where $\mathbf{U} \in M_{fc}$ is a fuzzy c-partition of X; $\mathbf{v} = (\mathbf{v}_1, \mathbf{v}_2, \cdots, \mathbf{v}_c)$ where $\mathbf{v}_i$ is the cluster center of prototype u_i, $1 \leq i \leq c$; and, u_{ik} is the membership of $\mathbf{x}_k$ in fuzzy cluster u_i. $J(\mathbf{U}, \mathbf{v})$ represents the distance from any given data point to a cluster weighted by that point's membership grade.
The solutions of

$$\min_{\mathbf{U} \in M_{fc}, \mathbf{v}} J(\mathbf{U}, \mathbf{v}) \qquad (5)$$

are least-squared error stationary points of J. The fuzzy clustering algorithm is obtained using the necessary conditions for solutions of (5), as summarized in the following:

Theorem 1: [1] Assume $|| \cdot ||$ to be an inner product induced norm: let $\mathbf{X}$ have at least $c < n$ distinct points, and define the sets ($\forall k$)

$$I_k = \{i | 1 \leq i \leq c; d_{ik} = ||\mathbf{x}_k - \mathbf{v}_i|| = 0\} \qquad (6)$$
$$\tilde{I}_k = \{1, 2, \cdots, c\} - I_k \qquad (7)$$

Then $(\mathbf{U}, \mathbf{v})$ is globally minimal for J only if (ϕ denotes an empty set)

$$I_k = \phi \Rightarrow u_{ik} = 1 \Big/ [\sum_{j=1}^{c} (\frac{d_{ik}}{d_{jk}})^p] \qquad (8)$$

or

$$I_k \neq \phi \Rightarrow u_{ik} = 0 \ \forall i \in \tilde{I}_k \ and \ \sum_{i \in I_k} u_{ik} = 1, \qquad (9)$$

and

$$\mathbf{v}_i = \sum_{k=1}^{n} (u_{ik})^2 \mathbf{x}_k \Big/ \sum_{k=1}^{n} (u_{ik})^2 \ \forall i \qquad (10)$$

The following iterative method is used to minimize $J(\mathbf{U}, \mathbf{v})$:
1. Initialize $\mathbf{U}^{(0)} \in M_{fc}$ (e.g., choose its elements randomly from the values between 0 and 1). Then at step l ($l = 1, 2, \cdots$):
2. Calculate the c fuzzy cluster centers $\mathbf{v}_i^{(l)}$ using (10) and $\mathbf{U}^{(l)}$.

2

3. Update $\mathbf{U}^{(l)}$ using (8) or (9).

4. Compare $\mathbf{U}^{(l)}$ to $\mathbf{U}^{(l-1)}$ using a convenient matrix norm, i.e., if $\|\mathbf{U}^{(l)} - \mathbf{U}^{(l-1)}\| \leq \varepsilon_L$ stop; otherwise, return to step 2.

5. Each node has c membership degrees with respect to the c clusters. Determine which cluster this node belongs to based on the maximum membership. By this means, every node is classified to one cluster and the network is partitioned to c clusters.

C. Clusterhead Election Using Fuzzy Logic Systems

Selecting an appropriate clusterhead can save power for the whole wireless sensor network. Generally, clusterhead election for sensor network is based on the distance to the centroid of a cluster, and the closest one is elected as the clusterhead; or pick a node with the maximum battery capacity as the clusterhead. A clusterhead receives data from nodes in its cluster and performs data aggregation, and transmits data to the gateway. So a clusterhead is much more energy-intensive than a regular node, and it's desirable that a clusterhead is located in the centroid (center) of a cluster so that all the other nodes can communicates with it with less energy consumption.

The clusterhead for each cluster can be elected based on the centroid of each cluster v_i $(i = 1, 2, \cdots, c)$, and the remaining power of each node. An ideal clusterhead should be very close to the cluster centroid and has very high remaining battery capacity. But generally both conditions are not satisfied at the same time. To compromise this, we apply a fuzzy logic system to clusterhead election.

C.1 Overview of Fuzzy Logic Systems

Figure 1 shows the structure of a fuzzy logic system (FLS) [10]. When an input is applied to a FLS, the inference engine computes the output set corresponding to each rule. The defuzzifer then computes a crisp output from these rule output sets. Consider a p-input 1-output FLS, using singleton fuzzification, *center-of-sets* defuzzification [11] and "IF-THEN" rules of the form

$$R^l : \text{IF } x_1 \text{ is } F_1^l \text{ and } x_2 \text{ is } F_2^l \text{ and } \cdots \text{ and } x_p \text{ is } F_p^l,$$
$$\text{THEN } y \text{ is } G^l.$$

Assuming singleton fuzzification, when an input $\mathbf{x}' = \{x_1', \ldots, x_p'\}$ is applied, the degree of firing corresponding to the lth rule is computed as

$$\mu_{F_1^l}(x_1') \star \mu_{F_2^l}(x_2') \star \cdots \star \mu_{F_p^l}(x_p') = T_{i=1}^p \mu_{F_i^l}(x_i') \quad (11)$$

where $\star$ and T both indicate the chosen t-norm. There are many kinds of defuzzifiers. In this paper, we focus,

for illustrative purposes, on the center-of-sets defuzzifier [11]. It computes a crisp output for the FLS by first computing the centroid, c_{G^l}, of every consequent set G^l, and, then computing a weighted average of these centroids. The weight corresponding to the lth rule consequent centroid is the degree of firing associated with the lth rule, $T_{i=1}^p \mu_{F_i^l}(x_i')$, so that

$$y_{cos}(\mathbf{x}') = \frac{\sum_{l=1}^M c_{G^l} T_{i=1}^p \mu_{F_i^l}(x_i')}{\sum_{l=1}^M T_{i=1}^p \mu_{F_i^l}(x_i')} \quad (12)$$

where M is the number of rules in the FLS. In this paper, we design a FLS for clusterhead election initiation.
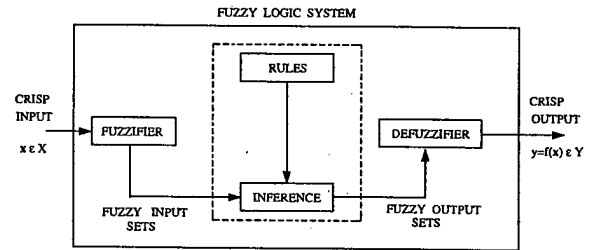

Fig. 1. The structure of a fuzzy logic system.

C.2 Clusterhead Election

The clusterhead is elected based on two descriptors: *distance of a node to the cluster centroid*, and *its remaining battery capacity*. The linguistic variables used to represent the distance of a node to the cluster centroid were divided into three levels: *near, moderate*, and *far*; and those to represent its remaining battery capacity were divided into three levels: *low, moderate*, and *high*. The consequent – the possibility that this node will be elected as a clusterhead – was divided into 5 levels, *Very Strong, Strong, Medium, Weak, Very Weak*. We used trapezoidal membership functions (MFs) to represent *near, low, far, high, very strong*, and *very weak*; and triangle MFs to represent *moderate, strong, medium*, and *weak*. We show these MFs in Fig. 2ab.

Based on the fact that a clusterhead should be very close to the cluster centroid and should have very high remaining battery capacity, we design a fuzzy logic system using rules such as:

R^l : IF *distance of a node to the cluster centroid* (x_1) is F_l^1, and *its remaining battery capacity* (x_2) is F_l^2, THEN the possibility that this node will be elected as a clusterhead (y) is G^l.

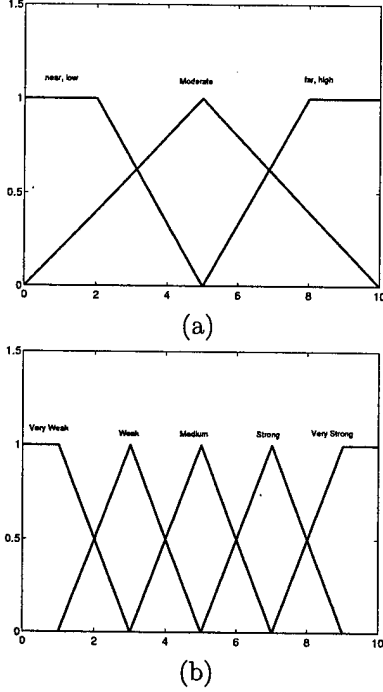where $l = 1, \ldots, 9$. We summarize all the rules in Table I.

3

Fig. 2. The MFs used to represent the linguistic labels. (a) MFs for antecedents, and (b) MFs for consequent.

Rule #	Antecedent 1	Antecedent 2	Consequent
1	near	low	medium
2	near	moderate	strong
3	near	high	very strong
4	moderate	low	weak
5	moderate	moderate	medium
6	moderate	high	strong
7	far	low	very weak
8	far	moderate	weak
9	far	high	medium

For every input (x_1, x_2), the output is computed using

$$y(x_1, x_2) = \frac{\sum_{l=1}^{9} \mu_{F_l^1}(x_1)\mu_{F_l^2}(x_2)c_{avg}^l}{\sum_{l=1}^{9} \mu_{F_l^1}(x_1)\mu_{F_l^2}(x_2)} \qquad (13)$$

By repeating these calculations for $\forall x_i \in [0, 10]$, we obtain a hypersurface $y(x_1, x_2)$, as plotted in Fig. 3.
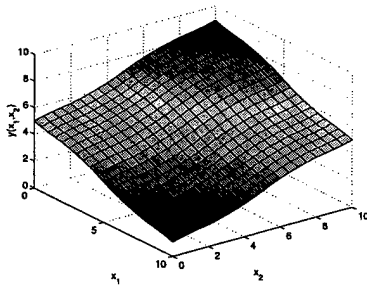

Fig. 3. The clusterhead election decision surface

We assume that hybrid TDMA and FDMA are used, i.e., different clusters work in different frequency band (FDMA), and nodes are coordinated using TDMA in each cluster. The clusterhead can set up a TDMA schedule and transmits this schedule to the nodes in its cluster. We assume perfect synchronization in this paper, so no collision will happen and the nodes which are not in transmission can stay in sleeping mode (the energy consumption is trivial).

III. TOPOLOGY UPDATED WITH RECONFIGURATION FOR MOBILE WIRELESS SENSOR NETWORK

A. A Mobility Management Scheme

A network protocol that can update its links to maintain strong connectivity with the mobile nodes is said to be "self-reconfiguring". There exist different mobility patterns in a mobile wireless sensor network:
1. nodes are moving in different directions with different speeds;
2. some nodes die out while others are mobile;
3. new nodes join in while others are mobile;
4. some nodes die out and some new nodes join in while other nodes are mobile.
In case 1, the total number of nodes doesn't change; and in cases 2-4, the number of nodes may change. Without loss of generality, we assume that the number of nodes and their locations may change from time to time. We dynamically and recursively update the partition of clusters based on the assumption that the number of clusters is constant. This approach is possible because our approach is an iterative optimization method. We summarize the procedures for updating the connectivity among nodes:
1. Collect the of status of each node including its geography information and its remaining battery capacity.
2. For every new node, randomly choose its membership degree to each cluster u^i and $\sum_{i=1}^{c} u^i = 1$. If a node dies out or leaves the network, delete its membership.
3. Update the total number of nodes n. Keep the existing c cluster centers $\mathbf{v}_i^{(l)}$ as the initial values for the

next iteration.

4. Calculate the c fuzzy cluster centers $\mathbf{v}_i^{(l)}$ using (10) and $\mathbf{U}^{(l)}$.

5. Update $\mathbf{U}^{(l)}$ using (8) or (9).

6. Compare $\mathbf{U}^{(l)}$ to $\mathbf{U}^{(l-1)}$ using a convenient matrix norm, i.e., if $\|\mathbf{U}^{(l)} - \mathbf{U}^{(l-1)}\| \leq \varepsilon_L$ stop; otherwise, return to step 4.

7. Each node has c membership degrees with respect to the c clusters. Determine which cluster this node belongs to based on the maximum membership. By this means, every node is classified to one cluster and the network is partitioned to c clusters.

8. Elect the clusterhead for each cluster based on the scheme presented in Section II-C.2.

9. Setup the star topology based on the partitioned clusters and elected clusterhead for each cluster.

The above procedure can be used by a network periodically for every short period of time since every node is mobile and its remaining battery capacity is time-varying.

B. Mobility Management with Hysteresis

In the network partition update (because of the mobility), a node will be switched to another cluster if the membership degree to its current cluster is less than the membership degree to another cluster. Similarly, a clusterhead will be switched if the election possibility for the current clusterhead is lower than one node in its cluster because of mobility and remaining battery capacity. Both schemes will have *ping-pong effect*, the repeated switch between two clusters caused by the rapid mobility.

Motivated by the handoff scheme in celluar networks [20], we modify the mobility management scheme with hysteresis, which allows a new clusterhead to be elected only if the election possibility of a new clusterhead candidate is sufficiently higher by a hysteresis margin. Similarly, the network partition with hysteresis will allow a node to switch to another cluster only if the membership degree to another cluster is higher enough by a hysteresis margin than the membership degree to the current cluster. This modification can prevent the *ping-pong effect*.

IV. Simulations

In our experiments, we used a 100-node wireless sensor network where nodes are randomly distributed between $(x = 0, y = 0)$ and $(x = 500m, y = 500m)$; each node has random battery level between J to $3J$ and an unlimited amount of data to communicate; and each node is mobile with different velocity from 0 to $1m/s$. Assume that a node will reverse its moving direction if it reaches the border.

In Fig. 4, we summarize the burst format we used. There are 480 QPSK symbols per burst, 10 guard symbols at the beginning and end of the burst; 24 public user information (PUI) symbols; 3 symbols unique word (UW) for training. and 433 symbols for payload. The random bits generator generates a binary data stream with equally likely zeros and ones, which are for the payload bits (866 bits). The burst builder can insert some header and control bits, and makes a complete burst with 960 bits, and then 960 bits are modulated to 480 QPSK symbols. It takes 5ms to transmit such a burst, so the symbol rate is $96ks/s$, and the information (payload) bit rate is 173.2kb/s. The channel bandwidth is set to 125KHz.

G	PUI	UW	Payload	G
10	24	3	433	10

Fig. 4. Burst format used in this paper.

We used the same model as in [3] for the radio hardware energy dissipation where the transmitter dissipates energy to run the radio electonics and the power amplifier, and the receiver dissipates energy to run the radio electronics. We chose the path-loss exponent $p = 2$. To transmit an l-symbol message a distance d, the radio expends:

$$E_{Tx}(l, d) = E_{Tx-elec}(l) + E_{Tx-amp}(l, d) = lE_{elec} + l\epsilon d^2 \tag{14}$$

and to receive this message, the radio expends

$$E_{Rx}(l) = E_{Rx-elec}(l) = lE_{elec} \tag{15}$$

The electronics energy, E_{elec}, as described in [3], depends on factors such as coding, modulation, pulse-shaping and matched filtering; and the amplifier energy, ϵd^2 depends on the distance to the receiver and the acceptable bit error rate. In this paper, we chose: $E_{elec} = 50nJ/sym$, $\epsilon = 10pJ/sym/m^2$. Same as [3][19], the energy for data aggregation is set as $E_{DA} = 5nJ/sym/signal$.

We applied our designing methodology to this senario. Initially, we partition the 100 nodes to 4 clusters (as validated in [3]) using FCM, and then elect the clusterhead for each cluster using the scheme described in Section II-C.2. Each node communicates directly with its clusterhead. In every 10 seconds, the topology is updated based on the iteration procedure proposed in Section III. The hysteresis margin was set to 0.5 (in 0 to 10 scale) for switching in clusterhead election, and the hysteresis margin for a node to change to another cluster was set to 0.05.

Energy is consumed whenever a node transmits or receives data or performs data aggregation. When a node uses up its energy, it dies out. Since the initial node locations and battery capacities were random, we ran Monte-Carlo simulations for 100 times. We compared our algorithm against the LEACH scheme proposed in [3], as plotted in Fig. 5. From this figure, we see that our scheme performs much better than the LEACH scheme. The possible reasons:

1. Our clusterhead election scheme considers the distance to the gateway as well as the remaining battery capacity.

2. FCM is a soft clustering algorithm, and it is realized via minimizing a cost function.

3. Hysteresis threshold can help to avoid abrupt changes in clusterhead election and cluster membership of nodes.
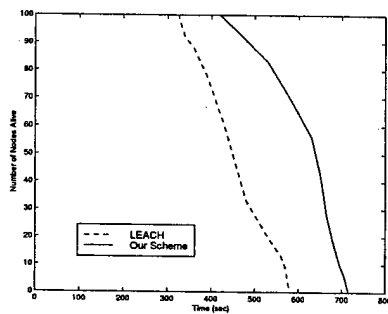

Fig. 5. The number of nodes alive versus time for our scheme and LEACH.

V. CONCLUSIONS

In this paper, we proposed a Fuzzy Energy Aware Topology Updated with REconfiguration for Sensornetworks (FEATURES). The sensor network is self-organized to clusters using a fuzzy c-means clustering for energy saving purpose. The clusterhead of each cluster is elected using a fuzzy logic system to maximize the network life. This topology is updated with reconfiguration to manage the mobility in mobile sensor networks since the the position of each sensor changes over time. We further modify this mobility management scheme with hysteresis to overcome the *ping-pong* effect. Simulation results show that our scheme performs much better than the Low-Energy Adaptive Clustering Hierarchy (LEACH) algorithm.

VI. ACKNOWLEDGEMENT

REFERENCES

[1] J. C. Bezdek, *Pattern Recognition with Fuzzy Objective Function Algorithms*, Plenum Press, New York, 1981.

[2] F. J. Block, and C. W. Baum, "An energy-efficient routing protocol for wireless sensor networks with battery level uncertainty," *IEEE Military Communications Conference*, Anaheim, CA, Oct 2002.

[3] W. B. Heinzelman, et al, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans on Wireless Communications*, vol. 1, no. 4, pp. 660-670, Oct 2002.

[4] T.-C. Hou and T-J. Tsai, "An access-based clustering protocol for multihop wireless ad hoc networks," *IEEE J. Selected Areas in Communications*, vol. 19, no. 7, pp. 1201-1210, July 2001.

[5] A. Iwata, C. C. Chiang, G. Pei, M. Gerla, and T. W. Chen, "Scalable routing strategies for ad hoc networks," *IEEE J. Selected Areas in Communications*, vol. 17, pp. 1369-1379, 1999.

[6] Q. Li, J. Aslam, and D. Rus, "Online power-aware routing in wireless ad-hoc networks," *Proc. of Annual ACM/IEEE International Conf. on Mobile Computing and Networking (MobiCom)*, Rome, Italy, pp. 97-107, 2001.

[7] C. R. Lin and M. Gerla, "Adaptive clustering in mobile wireless networks," *IEEE J. Selected Areas in Communications*, vol. 16, pp. 1265-1275, 1997.

[8] S. Lindsey, and C. S. Raghavendra, "PEGASIS: power-efficient gathering in sensor information systems," presented at *IEEE Aerospace Conference*, March 2002.

[9] S. Lindsey, K. Sivalingam, C. S. Raghavendra, "Power Optimization in Routing Protocols for Wireless and Mobile Networks," *Handbook of Wireless Networks and Mobile Computing*, Ed. Ivan Stojmenovic, John Wiley and Sons, 2001.

[10] J. M. Mendel, "Fuzzy Logic Systems for Engineering : A Tutorial," *Proceedings of the IEEE*, vol. 83, no. 3, pp. 345-377, March 1995.

[11] J. M. Mendel, *Uncertain Rule-Based Fuzzy Logic Systems*, Prentice-Hall, Upper Saddle River, NJ, 2001.

[12] C. E. Perkins, "Chapter 4, Cluster-Based Networks," *Ad Hoc Networking*, Edited by C. E. Perkins, pp. 75-138, Addison-Wesley, 2001.

[13] T. S. Rappaport, *Wireless Communications*, Prentice Hall, Upper Saddle River, NJ, 1996.

[14] V. Rodoplu, and T. Meng, "Minimum energy mobile wireless networks," *IEEE J. Selected Areas in Communications*, vol. 17, no. 8, pp. 1333-1344, Aug 2000.

[15] A. Safwat, H. Hassanein, and H. Mouftah, "Power-aware fair infrastructure formation for wireless mobile ad hoc communications," *Proc. of Globecom'2001*, pp. 2832-2836, San Antonio, TX, Sept 2001.

[16] C. Schurgers, V. Tsiatsis, S. Ganeriwal, and M. Srivastava, "Optimizing sensor networks in the energy-latency-density design space," *IEEE Trans. on Mobile Computing*, vol. 1, no. 1, pp. 70-80, Jan-Mar 2000.

[17] S. Singh, M. Woo, and C. S. Raghavendra, "Power-aware routing in mobile ad hoc networks," *Proc. of Annual ACM/IEEE International Conf. on Mobile Computing and Networking (MobiCom)*, Dallas, TX, pp. 181-190, 1998.

[18] K. Sohrabi, et al, "Protocols for self-organization of a wireless sensor network," *IEEE Personal Communications*, vol. 7, no. 5, pp. 16-27, Oct 2000.

[19] A. Wang, et al, "Energy-scalable protocols for battery-operated microsensor networks," *Proc of IEEE Workshop on SIgnal Processing Systems (SiPS'99)*, Taipei, Taiwan, Oct 1999, pp. 483-492.

[20] N. Zhang, and J. M. Holtzman, "Analysis of handoff algorithms using both absolute and relative measurements," *IEEE Trans. Vehi. Technol.*, vol. 45, pp. 174-179, Feb. 1996.

6

An Access-Based Low-Energy Hierarchy for Sensor Networks

Liang Zhao
Department of Electrical Engineering
University of Texas at Arlington
Arlington, TX 76010, USA
Email: zhao@wcn.uta.edu

Qilian Liang
Department of Electrical Engineering
University of Texas at Arlington
Arlington, TX 76010, USA
Email: liang@uta.edu

Abstract— We consider the clustering criterion for a wireless sensor network to minimize the communication related energy dissipation. Based on Minimum Communication-related Energy Dissipation criterion, we show that the optimal cluster size n is linear proportional to the node distribution density ρ. This result leads us to introduce n *rule* as clustering rule, which divides the whole network into clusters with about n members and n adaptively determined by local density ρ. Using n rule, we propose an Access-Based Low-Energy Hierarchy(ABLEH) to make clustering protocols more adaptive to the dynamic nature of sensor networks. Simulation results show that about 50% reduction can be achieved in energy dissipation and effective system lifetime are extended tremendously compared with LEACH.

I. INTRODUCTION

A wireless sensor network can be thought of as an ad hoc network consisting of sensors linked by a wireless medium to perform distributed sensing tasks. Sensor networks are very similar to ad hoc networks as viewed from telecommunication technology, but there are some vital differences such as that the sensors are densely deployed and limited in power [1], thus the protocols developed for traditional wireless ad hoc networks are not well suited to the unique features of sensor networks. When a sensor node may have to operate for a relatively long duration on a tiny battery, energy efficiency becomes a major concern.

In the wireless sensors, the energy is dissipated in receiving, aggregating and transmitting signals. Such energy dissipation is called "Communication-related Energy Dissipation"(CED) in this paper and is what we aim to minimize. There could be other use of energy such as driving the sensing devices. Such Non-Communication Energy Dissipation is out of the scope of this paper.

A variety of "power-aware" routing protocols have been proposed to address this problem. In one school of thought [2]–[4], the traditional Shortest Path First strategy is replaced by Least Energy First routing, i.e., a multihop route is preferred to a single-hop one if only multiple short-distance relays cost less energy than a single long-distance transmission. For example, "Minimum Transmission Energy"(MTE) routing [3], [4] was proposed in place of traditional "minimum hops routing". Another school of thoughts is that nodes are clustered so that a hierarchy is formed. LEACH [16], an example of the latter school, can improve system lifetime by an order of magnitude compared with general-purpose multihop approaches.

Unfortunately, the network model LEACH base itself on is basically a static one, in which nodes is always on and they always have data to send to the base station. In fact, topology changes are frequent in sensor networks and can be attributed to node mobility and shutdown/failure. LEACH suffers drastically in these time-varying topologies. To address the effect of changing topology on clustering protocols, a thorough study of clustering based on Minimum Communication-related Energy Dissipation criterion (MCED) has been successfully attempted and the resulting n rule is presented in this paper.

The paper is organized as follows. Section II reviews background and related work. We introduce the new clustering criterion termed n *rule* in Section III and present a clustering protocol using such criterion in Section IV. Simulations are given in Section V, and Section VI concludes this paper.

II. PRELIMINARIES

In this section, we provide some preliminaries that are needed for the rest of this paper.

A. Clustering

Based on the observations on cellular networks [5]–[13], [19], it would be advisable to partition nodes into clusters for the reasons listed below.

a. **Spatial reuse** If two clusters are far enough, they may use the same channels. This increases the system capacity and may be especially useful when sensor nodes are densely deployed.

b. **Less update cost** When any changes happen to the network topology, corresponding update must be taken to inform related nodes. Generally, the update cost increases with the network size. In the clustered hierarchy, the updates are only local and hence largely reduced.

c. **Less routing information** It is well known that a proper hierarchy can lessen the generation and propagation routing information, which implies less energy usage.

d. **Less Data Transmission** Since the sensors are densely deployed, there is a lot of redundancy in the data collected by the neighboring sensors. It is not necessary to send all these data to the base station. If the sensor network

is clustered, the cluster leader can perform data fusion to reduce the date send back to the base station and hence reduce the overall energy. Since the transmission energy is exponentially proportional to the distance as discussed in II-C, energy could be saved by collecting data from neighboring nodes and then transmitting aggregated data by one long distance transmission.

In previous ad hoc networks research, there is a dispute whether a clusterhead should be elected within each cluster. Some researchers [5], [9], [10] argue that it is unreasonable to have a cluster leader as every node has similar energy constraint and the leader will consume energy much faster. Their methodology breaks the information exchange into two parts; cluster members proactively perform the intracluster exchange, and intercluster information exchange is achieved by demand-based operations. This approach does have some advantage where the traffic is basically within the cluster, however, since most traffic in sensor networks is directed from sensor nodes to the base station, i.e., of intercluster type, headless structure suffers drastically. On the other hand, the extra burden of clusterhead can be mitigated by rotating the headship among the members. The rotation can also take advantage of the relaxation effect [17], which indicates frequently reducing the current drawn from the battery enables the battery to recover a portion of its lost capacity and hence lengthens the battery lifetime.

B. Lifetime Model

In [16], the always-ON model is utilized, in which the nodes are supposed to be always active and have data to transmit. To save energy, the nodes in real applications are often set to alternate between active and inactive states. And the nodes may have no data for transmission, which can be regarded as inactive. Thus, ON-OFF model may be a better approximation of the lifetime model [14], in which the active and sleeping time of nodes obey the exponential probability law with mean T_a and T_s respectively. Thus, the average number of active nodes is

$$E[N_a] = T_a/(T_a + T_s). \tag{1}$$

C. Radio Energy Dissipation

According to the path loss model [19], the energy required to transmit over a distance d is $E \sim d^\beta$, where β is the pass loss exponent, whose value depends on the specific propagation environment. For example, β will have a larger value for long distance transmission than for short distance transmission. To save energy and reduce interference, the power control is widely utilized in wireless communications [19]. That is to say, the radio can be adjusted for a range of output power level. For example, the maximum transmission radius R_{max} is achieved at the maximum output power level, which may be used in broadcasting vital information, but in most cases, for energy economy, the node would like to choose a lower output power level resulting in a less range R_c. We will prove in Section III-B there exists an optimal R_c for given node distribution in least energy dissipation sense.

The model of the radio hardware energy dissipation used in our simulations is adopted from [16], which indicates that to transmit l bits over distance d, the radio expends

$$E_{TX}(l,d) = \begin{cases} lE_{elec} + l\epsilon_{fs}d^2, & d < d_0 \\ lE_{elec} + l\epsilon_{mp}d^4, & d \geq d_0 \end{cases} \tag{2}$$

and to receive l bits over the same distance, the radio expends

$$E_{RX}(l,d) = lE_{elec} \tag{3}$$

And the communication energy parameters are set as

$$E_{elec} = 50nJ/bit$$
$$\epsilon_{fs} = 10pJ/bit/m^2$$
$$\epsilon_{mp} = 0.0013pJ/bit/m^4 \tag{4}$$

D. Channel Assignment

The term channel, in one of its narrow sense, means a band of frequency which is assigned to a user for exclusive usage. In wide sense, it could be referred to a time slot or a spread spectrum code. To increase capacity and minimize interference, a variety of channel assignment strategies have been developed and can be classified as fixed, dynamic or adaptive. [19]

In a Fixed Channel Assignment strategy (FCA), each user or group is allocated a predetermined set of channels. Any transmission attempt can only succeed by the channel granted. If all the channels are occupied, no new user can receive service. On the other hand, in Dynamic Channel Assignment strategy(DCA), channels not allocated permanently, but assigned and released on request. DCA can make better use of channels while introducing more protocol overhead and channel management. A trade-off is Adaptive Channel Assignment (ACA), in which a division of channels are assigned to current users in a fixed manner while the rest of channels are reserved for prospective users and will be assigned on demand. ACA not only moderates the waste of channels in FCA but also reduces protocol overhead and channel management.

III. n Rule: Decentralized Clustering

Clustering has been widely used in pattern recognition, and in most cases, the Minimum Mean Square Error (MMSE) is used as the clustering criterion. However, in sensor networks, clustering is utilized to form a energy-efficient hierarchy. Thus, Lease Communication-related Energy will be aimed in place of MMSE. Starting with this goal, we will derive the corresponding optimal clustering rule, termed as n rule, in this section.

A. Clustering Criterion

The typical scenario is that N nodes are uniformly distributed in a region with dimension of $M \times M$, then, the node

distribution density ρ is a constant and given by

$$\rho \overset{\Delta}{=} \frac{\text{number of nodes}}{\text{area of the occupied region}} \quad (5)$$

$$= \frac{N}{M \times M} \quad (6)$$

The traditional cluster algorithms such as K-means partition nodes into k clusters, where k is a predefined number. For convenience, such strategy will be called k rule in the following. We propose a different strategy named n rule, which is to divide nodes into clusters with average size of n (hence the name). The two rules are theoretically equivalent, because under uniform distribution, n is related to k are related by

$$n = N/k \quad (7)$$

[16] indicates the optimal value of k is given by

$$k^* = \sqrt{\frac{N\epsilon_{fs}}{2\pi\epsilon_{mp}} \frac{M}{d_{toBS}^2}} \quad (8)$$

Based on (6) and (8), the optimal value of n in 7 can be obtained as

$$n^* = \frac{\rho}{\sqrt{2\pi}} \sqrt{\frac{\epsilon_{mp}}{\epsilon_{fs}}} d_{toBS}^2 \quad (9)$$

The optimal clustering criterion developed above points out that from a global point of view, k is mainly determined by N, M and d_{toBS}, i.e.,

$$k = F_k(N, M, BS),$$

where BS is the coordinates of the Base Station, or from a local point of view, n is mainly determined by the node distribution density and the distance to the base station, i.e.,

$$n = F_n(\rho, BS).$$

The localization in n rule has some fundamental effects in practice.

The first effect is that k is relevant with both N and the area $M \times M$, which as global information can only be obtain at the price of other routing protocols. On the other hand, as shown in (9), the parameter ρ that n depends on can be estimated locally. Using n rule eliminates the dependency on other routing protocols, which not only simplifies the architecture but also reduces the latency and speeds up the convergence. Especially when the network size increases, the advantage of n rule become more intense.

In real applications, the relationship are not computed mathematically from (8) or (9), but represented by a table compiled from empirical data. Since the n table is smaller in size, it needs less memory to implement and quicker to look up. Furthermore, in practice, N and M may be both situation and application dependent, while ρ is only application dependent and thus less variable, which amplify the gain on the table size.

k rule requires the knowledge of overall N, M available to each node, which can only be obtained at a distinct disadvantage. On the contrary, what the n rule needs is ρ, which can be estimated by local node distribution density

$$\rho_t = \frac{N_t}{\pi R_t^2}, \quad (10)$$

where N_t is the number of nodes in the transmission region, and the R_t is the transmission radius. When transmission range is large enough, ρ_t approaches ρ closely.

It would be a natural question why n-rule clustering algorithms do not appear until recent research on sensor networks. The reason for this lies in the different criteria. The traditional clustering algorithms such as K-means are all based on MMSE criterion, while n rule is aimed to minimize the Communication-related Energy Dissipation. Consider an extreme case, if large amount of nodes are gathered in one corner, it is logic to cluster these nodes into the same cluster under MMSE criterion as they exhibit visible similarity. But now, the major motive of applying clustering to sensor networks is energy efficiency. As shown in V-A, large cluster size compromises energy efficiency as the head may be exhausted quickly when it has to receive and aggregate large amount of data from its excessive number of members. Therefore, it would be advisable to divide the gathered nodes into more clusters instead of single one.

B. Optimal Cluster Size

Although rectangle coordinates are widely used in current sensor networks research, we choose polar coordinate for reasons listed below. Although the region of interest can be of any shape, many phenomena show a approximately central symmetry and the interest generally decreases with the distance from the phenomenon of interest. Also considering the required transmission power increase with the distance, it is only logical to utilize polar coordinates. Furthermore, many problems of interest in related research can be simplified by choosing polar coordinates. For example, consider the optimal positions of five cluster heads. Due to the central symmetry, these positions must be on the same ring or one of them is at the origin. Then, the only unknown to be found is the radius of such ring. On the contrary, although the (x, y) coordinates also come in symmetry in rectangle coordinates, there are much more unknowns left and it needs more effort to solve.

The energy dissipation model we develop here is adopted from [16], where rectangle coordinates are utilized. Assume that there are N nodes distributed uniformly in a circular region with radius of R. Thus, according (5), the node distribution density is

$$\rho = \frac{N}{\pi R^2} \quad (11)$$

Suppose a cluster algorithm divide nodes into cluster with size n, then there are $\lceil N/n \rceil$ clusters with one clusterhead and $n-1$ non-head members in each cluster. The power dissipated in the cluster head node is

$$E_{CH} = lE_{elec}(n-1) + lnE_{DA} + l(E_{elec} + \epsilon_{mp}d_{toBS}^4) \quad (12)$$

where l is the bits each sensor collects in a round, d_{toBS} is the distance from the cluster head node to the base station.

The energy used in each non-head node is

$$E_{non-CH} = lE_{elec} + l\epsilon_{fs}d_{toCH}^2 \tag{13}$$

where d_{toCH} is the distance from the non-head node to the corresponding head. Assume the area occupied by a cluster is circular and is approximately $\frac{\pi R^2}{N/n}$, then the cluster radius is

$$R_c = R\sqrt{\frac{n}{N}}. \tag{14}$$

Assuming the node head is at the center of mass of the cluster,

$$\begin{aligned}
E[d_{toCH}^2] &= \int\int r^2\rho(r,\theta)rdrd\theta \\
&= \int_0^{2\pi}\int_0^{R_c} r^2\rho(r,\theta)rdrd\theta \\
&= \frac{\pi\rho R^4 n^2}{2N^2} \tag{15}
\end{aligned}$$

Substituting $\rho = N/(\pi nR^2)$ into (15),

$$E[d_{toCH}^2] = \frac{\pi nR^2}{N} \tag{16}$$

Therefore, the total power dissipated in each cluster is

$$\begin{aligned}
E_{cluster} &= E_{CH} + (n-1)E_{non-CH} \\
&\approx P_{CH} + nP_{non-CH} \tag{17}
\end{aligned}$$

and the total power dissipated in the whole network is

$$\begin{aligned}
E_{total} &= \frac{N}{n}E_{cluster} \\
&= Nl\{E_{elec} + E_DA + \frac{1}{n}\epsilon_{mp}d_{toBS}^4 \\
&\quad + E_{elec} + \epsilon_{fs}\frac{\pi nR^2}{N}\} \tag{18}
\end{aligned}$$

The optimal n is found by letting $\frac{\partial E_{total}}{\partial n}$ to zero,

$$n^* = \sqrt{\frac{N\epsilon_{mp}}{\pi\epsilon_{fs}}}\frac{d_{toBS}^2}{R} \tag{19}$$

For our experiments, the base station is located at $(r_{BS}, \pi/2) = (125, \pi/2)$, then d_{toBS}^2 can be estimated by

$$\begin{aligned}
E[d_{toBS}^2] &= \int\int |r - r_{BS}|^2\rho(r,\theta)rdrd\theta \\
&= \frac{1}{\pi R^2}\int_0^{2\pi}\int_0^R (r^2 + r_{BS}^2 \\
&\quad -2rr_{BS}cos(t - \pi/2))rdrdt \tag{20} \\
&= 20625 \tag{21}
\end{aligned}$$

By substituting (21) into (19), we obtain

$$n^* \approx 13.2675. \tag{22}$$

According to (14), the corresponding energy-economic transmission radius, i.e. optimal cluster size is

$$R_c^* = 36.4246(m) \tag{23}$$

Although n rule has application importance as discussed in Section III-A, n and k are theoretically interchangeable as long as uniform node distribution assumption hold. In the following discussion, n or k is chosen for the convenience, for example, (22) is equivalent to $k^* \approx 7$.

IV. ACCESS-BASED LOW-ENERGY HIERARCHY

Based on the discussion in Section III, we propose the Access-Based Low-Energy Hierarchy (ABLEH). It is especially designed for energy efficiency and higher tolerance to topology changes. And for higher tolerance to interference, low detectability and multiple access communication by a large population of relatively uncoordinated users [20], Direct Sequence Spread Spectrum is utilized in ABLEH. Some Spread Spectrum codes may be set aside as public channels, and each cluster has its own Spread Spectrum code so that the interference between clusters is minimized. For intracluster communications, TDMA is used with Adaptive Channel Assignment (ACA). Specifically, when a cluster is formed, the clusterhead create a time schedule and broadcast it to its member. As shown in Fig.2, each member is assigned a time slot per frame to send its data to the clusterhead, and the extra time slots are reserved for prospective members. Due to the low data rate of sensor networks, there is always enough free slots for reservation. The state transition diagram is shown in Fig.1. All nodes start at the stand-alone state, broadcasting its vital information at the maximum output power level. Then based on these information, the strongest are elected as clusterheads and others join the closest cluster according to received signal strength. A non-head member may doze off according to its schedule. When a new sensor node comes to, it tries to join a cluster. It broadcasts its own vital information and eavesdrops the public channel for STANDY-BY duration. If it finds some nearby clusterheads, it will choose the one with strongest received signal strength as its clusterhead. Otherwise, it elects itself as clusterhead and starts recruiting other nodes. When the round ends, the nodes return to stand-alone state and a new round will begin.

A. Information Exchange

The vital information needed to be exchanged may include battery level, estimated battery life, etc. What's more, the nodes can estimate the distance to other nodes by the received signal strength according to the path loss model given that the output power level is known a priori. In ABLEH, the information exchange is totally based on access, that is to say, there is no routing or relaying of these information. Each node maintain a neighbor list to record the aforementioned information. In case some nodes lost these information, they would retrieve the neighbor list from their clusterhead.

B. Head Election

Similarly to LEACH, each node elects itself as clusterhead by the probability of $k^*E(i)/E_{total}$, where $E(i)$ is the node's own energy, E_{total} is the total energy and k^* is the optimal number of clusters. As shown in Section III-B, k^* depends

on ρ and other parameters. But there is no way for nodes to know the number of active nodes in the whole network. Thus, LEACH has to base on the predetermined parameter N. Although the average number of active nodes, $E[N_a]$, can be calculated by (1) in experiments, such estimation is impossible in real application as the average active and sleeping time are unknown before the nodes are deployed to observe the phenomenon of interest. In fact, the k^* is set to five in the experiments presented in [16]. When the number of active nodes keeps varying, the fixed k^* can not achieve the energy economy. Therefore, in ABLEH, k^* is adaptively estimated according to (19). As a result, no mater how the number of active number changes, the ABLEH maintains the optimal clustering criteria.

C. Cluster Formation

Based on the received signal strength, the non-head nodes chooses the nearest clusterhead and send a "Request-to-join" message to the clusterhead. The clusterhead waits for a 3T duration before it creates the time schedule. In the schedule, time slots are set aside for intracluster communication, data aggregation, intercluster communication and maintenance. Since an effective cluster radius is always smaller than the maximum transmission radius as assumed in [16] (otherwise the sensor nodes may be unable to communicate peer-to-peer), the neighbor lists at nodes of the same cluster are identical, thus, there is no need to exchange the neighbor list during the cluster formation.

D. Steady State

After the clusters are formed, the sensor network enter the steady-state phase. The clusterhead receive data from members, perform data aggregation and then send the resulting data back to the base station. There is some special time slots for maintenance, for example, the clusterhead can turn off radio and perform data aggregation for some slots and sends out advertisements at another slot.

V. SIMULATIONS

In this section, we compare the performance of ABLEH and LEACH using computer simulations. 100 nodes are uniformly distributed in a circular region with radius of 100 m, and the base station is located at $(r_{BS}, \pi/2)$, where $r_{BS} = 125$ m.

A. Case 1

In this case, we used LEACH to study the average energy dissipation per round with varying k. Every node was given 300 J energy so that steady-state statistics can be collected. Unfortunately, LEACH can not ensure the elected head is exactly as desired. Consider the typical case presented in III-A, every node elect itself as head with probability $p = k^*/N = 5\%$. The probability of that outcome match expected is

$$P(k = 5) = \binom{N}{k}p^k(1-p)^{N-k}$$
$$= \binom{100}{5}0.05^5(1-0.05)^{100-5} = 18\% \quad (24)$$

To evaluate the effect of k on energy efficiency, we let node repeat election until the desired number of clusters was

achieved. The resulting average energy dissipation per round is shown in Fig.3, which indicates there exists an optimal range. And when k leaves optimal range slightly, the energy dissipation increases, but the increase is tolerable unless the k is far away from the optimal value. Note that the optimal k approximately matches the estimated k^*. The analytical results in Section III-B are also verified.

B. Case 2

In this case, the system lifetime was evaluated. Initially, each node had 2 J energy. We ran 1000 simulations and plotted received data and the number of surviving nodes in Fig.4 and 5. Fig.4 shows the data received by the base station versus amount of energy dissipation. Observe that ABLEH can deliver about half more data than LEACH with the same amount of energy dissipation. In Fig.5, the number of alive nodes versus data received in the base station is plotted. Note that during the last stage, the curve plumbs down quickly. During this critical stage, dying nodes tried in vain to organize themselves while virtually no data are received by the base station. By comparing the critical stage, Fig.5 clearly demonstrates that ABLEH extends network lifetime by around 50%.

VI. CONCLUSION

In this work, we studied the clustering issues in sensor networks based on Minimum Communication-related Energy Dissipation criterion and introduced n rule, which is distinct from traditional clustering algorithms derived on MMSE criterion. As an application of n rule, Access-Based Low-Energy Hierarchy is proposed and compared against LEACH. According to our observation, the localization favors the energy efficiency. Although many clustering algorithms is to aim the localization, this goal is often lost in the design. For example, the dependency on the global information composes a fatal drawback to LEACH and other clustering protocols. Topology changes also introduce more problems to clustering protocols. Localization is still the key to these problem. Thanks to the inherent localization of n rule, simulations show about 50% improvement in terms of data received per energy and effective lifetime.

VII. ACKNOWLEDGMENT

REFERENCES

[1] I. Akyildiz et al., "A survey on sensor networks," *IEEE Commun. Magazine*, pp.102-114, Aug. 2002
[2] R. Min et al., "Energy-Centric Enabling Technologies For Wireless Sensor Networks," *IEEE Wireless Commun.*, pp 28-39, Aug. 2002
[3] T. Shepard,"A channel access scheme for large dense packet radio networks," in *Proc. ACM SIGCOMM*, Stanford, CA, Aug. 1996, pp.219-230.
[4] M. Ettus, "System capacity, latency and power consumption in multihop-routed SS-CDMA wireless networks," in *Proc. Radio and Wireless Conf. (RAWCON)*, Colorado Springs, CO, Aug. 1998, pp.55-58.

5

[5] C. R. Lin and M. Gerla, "Adaptive clustering for mobile wireless networks",*IEEE J. Select. Ares Commun.*, vol. 15, pp. 1265-1275, Sept. 1997 D. J. Baker, "Distributed control of broadcast radio networks with changing topologies," in *Proc. IEEE Infocom*, San Diego, CA, Apr. 1983, pp.49-55.

[6] B. Das and V. Bharghavan, "Routing in ad-hoc networks using minimum connected dominating sets," in *Proc. IEEE Int. Conf. Communications*, Montreal, QC, Canada, June 1997, pp. 376-380.

[7] B. Das, R. Sivakumar, and V. Bharghavan, "Routing in ad hoc networks using a spine," in *Proc. IEEE computer Communications and Networks*, pp.34-39,Sept. 1997.

[8] R. Ramanathan and M. Steenstrup, "Hierarchically-organized, multihop mobile wireless networks for quality-of-service support," *Mobile Networks Appl.*, vol. 3, no. 1, pp. 101-119,1998

[9] A. B. McDonald and T. F. Znati, "A mobility-based framework for adaptive clustering in wireless ad hoc networks," *IEEE J. Select. Areas Commun.*, vol. 17, pp. 1466-1487, Aug. 1999

[10] N. H. Vaidya et al., "A cluster-based approach for routing in dynamic networks," *ACM Comput. Commun. Rev.*, vol. 17,no. 2, Apr. 1997.

[11] A. J. Haas and B. Liang, "Ad hoc mobility management with uniform quorum systems," *IEEE/ACM Trans. Networking*, vol. 7, pp. 228-240,Apr. 1999.

[12] W. Chen, N. Jain, and S. Singh, "ANMP:Ad hoc network management protocol," *IEEE J. Select. Areas Commun.*, vol. 17,pp.1506-1531,Aug. 1999

[13] A. Iwata et al., "Scalable routing strategies for ad hoc wireless networks," *IEEE J. Slect. Areas Commun.*, vol. 17,pp.1369-1679,Aug. 1999

[14] T.-C. Hou and T.-J. Tsai, An Access-Based Clustering Protocol for Multihop Wireless Ad Hoc Networks, *IEEE J. Select. Areas Commun.* , vol. 19, pp. 1201-1210, Jul. 2001

[15] K. Sohrabi et al, Protocols for Self-Organization of a Wireless Sensor Network, *IEEE Personal Communications*, pp16-27, Oct. 2000

[16] W. B. Heinzelman et al, An Application-Specific Protocol Architecture for Wireless Microsensor Networks, *IEEE Trans. On Wireless Communications*, Vol. 1, No. 4, Oct. 2002

[17] C.F. Chiasserinia and R.R. Rao, "Pulsed battery discharge in communication devices", *Proc. Mobicom*, pp.88-95, 1999

[18] J. Manyika and H. Durrrant-Whyte, *Data Fusion and Sensor Management: A Decentralized Information-Theoretic Approach*, Ellis Horwood Limited, 1994

[19] T. S. Rappaport, *Wireless Communications:Principles and Practice*,2nd ed. Upper Saddle River, NJ: Prentice-Hall, 2002.

[20] A.J. Viterbi, *CDMA:principles of spread spectrum communication*, Addison-Wesley Publishing Company, 1995
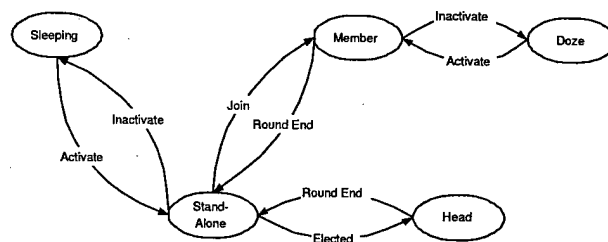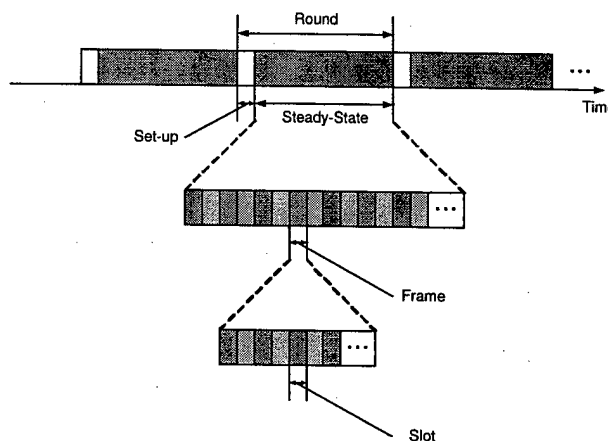
Fig. 1. State transition diagram of a node in ABLEH

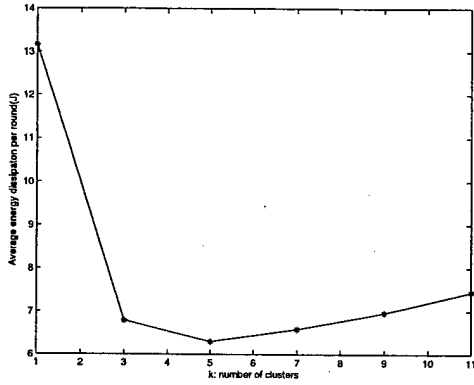

Fig. 2. Time line showing ABLEH's frame structure.

6

Fig. 3. Average energy dissipated per round in LEACH versus k. This graph shows the optimal range of k is between 3 and 7.
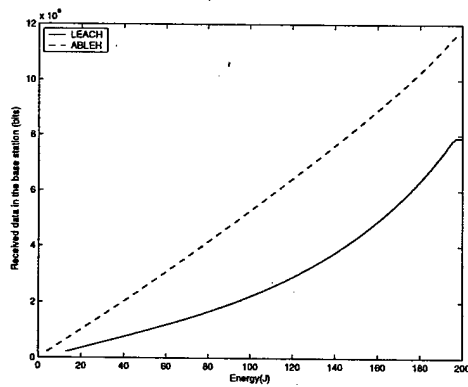

Fig. 4. Data for 2J initial energy simulations. Total amount of data received at the BS per amount of dissipation. ABLEH delivers 150% amount of data to the BS as LEACH for the same amount of dissipation.
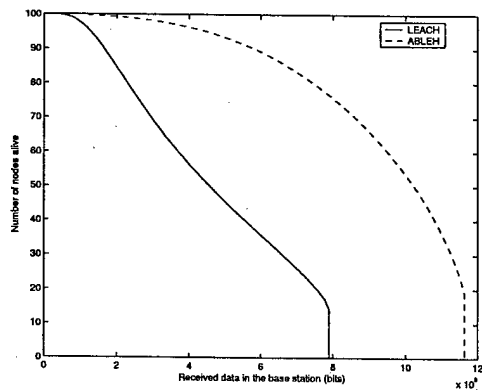

Fig. 5. Data for 2J initial energy simulations. Number of nodes alive per amount of data sent to the BS. ABLEH delivers 150% amount of data to the BS as LEACH for the same number of node deaths.

An Access-Based Energy Efficient Clustering Protocol for Large Scale Wireless Sensor Network

Xiang Hong
Department of Electrical Engineering
University of Texas at Arlington
416 Yates Street
Nedderman Hall, Rm 518
Arlington, TX 76019
Email: hong@wcn.uta.edu

Qilian Liang
Department of Electrical Engineering
University of Texas at Arlington
416 Yates Street
Nedderman Hall, Rm 518
Arlington, TX 76019
Email: liang@uta.edu

Abstract—The ad hoc wireless sensor network is usually deployed in severe environment with limit power supply, whose topology is dynamic and flexible without any fixed infrastructure. In order to facilitate the management and routing, many algorithms have been proposed to partition mobile sensor nodes into clusters. In this paper we developed an Access-Based Energy Efficient clustering protocol (ABEE), whose clustering algorithm is based on the outcome of the multiple access to the public channel. ABEE retains the advantage of access-based scheme such as self-organization, flexibility and stability. Also by considering the energy dissipation during the compression and transmission of the collected data, ABEE can provide uniformly distributed and energy efficient infrastructure for the upper lever protocols. We also propose to use coverage area to judge the robustness of the network as well as the number of active nodes. Simulation is used to compare ABEE with the exclusively access-based clustering protocol in terms of rationality of the cluster structure, system lifetime and the coverage area. Our result shows that the ABEE can partition the large scale of nodes more rationally, efficaciously improve the system lifetime and the coverage area of the whole network.

I. INTRODUCTION

As the speedy development of the low-power electronics, RF (radio frequency) circuits and MEMS design, the wireless sensor network probably will be widely deployed in the commercial and military applications. A lot of functions can be integrated into a small board of sensor, which can collect sorts of data such as temperature, light, voice even video. These low-cost sensors can construct a reliable monitoring system for a certain territory, which shows bright future in the applications such as surveillance, battle field reconnaissance and chemical/biological detection.

Because the whole system should be able to operate without a fixed infrastructure and be deployed rapidly to support emergency requirement or undeveloped area, the network management, resource allocation and routing strategies become challenges to the protocol designers. In order to achieve better performance of network management, many schemes have been proposed, among which the cluster architecture for an ad hoc network obviously has three main advantages. First, in the multi-hop environment, a cluster structure facilitates the spatial reuse of resources to increase the system capacity [1]- [8]. The

second advantage comes from the dynamic topology update [6], when a mobile node changes its position, it is sufficient for only the nodes in its cluster to update the topology information, not all in the system. The third advantage is on routing where the generation and propagation of routing information can be reduced [8]- [9]. Cluster head is the upper level backbone to support sorts of routing.

In order to get optimal clustering protocol, three important parameters are relative to the performance of the whole sensor network.

A. System lifetime

Because of the dangerous environment where the sensor nodes may be deployed, the battery of the nodes can not be recharged or replenished easily. These networks should operate as long as possible. So the whole system infrastructure should be more energy efficient.

B. Deployment

The number of sensor nodes in an ad hoc wireless network may be hundreds. These nodes are deployed in remote and severe environment to replace human being to collect information. It may be impractical to set up a central control base station in the target area to supervise or maintain the topology of the network [5]. It means all the nodes should be self-organized to form a more rational infrastructure to facilitate network management.

C. Correlation among nodes

The notion of "quality" in a sensor network is very different than in traditional wireless data networks [10]. For sensor networks, the end user does not require all the data in the network because 1) the data from neighboring nodes are highly correlated, making the data redundant and 2) the end user cares about a higher-level description of events occurring in the environment being monitored. It means that we can compress the coarse data in the cluster head to reduce the throughput of the higher hierarchy.

In our work, considering large-scale ad hoc wireless sensor network, we design an Access-Based Energy Efficient Cluster

Algorithm (ABEE) from protocol point of view, to satisfy the aforementioned key factors of the network. This protocol treats all the nodes identical and they can be either the cluster head or cluster member based on the order of the channel access. We use the Collision Sense Multiple Access with Collision Avoidance(CSMA/CA) as the MAC layer communication scheme. ABEE provides rules of communication during the cluster formation in which all cluster member nodes are within one hop away to their cluster head.

The paper is organized as follows. Section II provides background and related work. Section III gives the core algorithm and the architecture of ABEE protocol. Simulations are given in Section IV and Section V concludes the paper.

II. PRELIMINARIES

We first review the prototype of the access-based clustering protocol. Next, the energy dissipation model during the data transmission will be given.

A. Prototype of the access-based clustering protocol

Access-based clustering protocol (ABCP) [11] is a simple broadcast request-response protocol with first-come-first-serve selection that is coupled with a probabilistic contention resolution scheme. ABCP proposed that there is no central base station to control the initial topology of the network. All nodes are identical and can be either cluster head or cluster member. Every node begins as an ordinary node and sends the REQ_TO_JOIN message to all the neighbors to request to join a cluster. If there is no $HELLO$ message from the existing cluster head after a certain time up, the ordinary node will try to send $HELLO$ message and become a cluster head. If it receives a $HELLO$ message, it will send $JOIN$ message to cluster head that sends the $HELLO$ message. After receives ACK message from the cluster head to confirm, it becomes a cluster member of the cluster head. In order to reduce the number of isolated cluster head, the cluster head without any member will try to switch back to the ordinary node and join another cluster. ABCP does provide rapidly deployed and stable clustering algorithm in terms of protocol. However, because ABCP is self-organized and based on the stochastic access of the channel, it is possible that initially two cluster heads are very close and both have just a few cluster members, which will increase the number of clusters and is malicious to the uniformity of the distribution of the clusters. The topology uniformity of the cluster is very crucial in the energy depletion during the data transmission. Energy depletion will substantially affect the lifetime of the whole network. In order to prolong the lifetime of the whole network, a more rational distribution of clusters should be taken of great consideration.

B. Energy dissipation model during the data transmission

According to [10], all the member nodes are within one hop away from their corresponding cluster head, the free space (d^2) power loss model will be used. In this paper, we assume the distance between the base station and the deployed network

is far enough to apply the multi-path fading (d^4)power loss model [12]. The energy depletion for one cluster member node during the transmission of an K bits packet will be,

$$E_{tx} = K \cdot E_{elec} + K \cdot \epsilon_{fs} \cdot d^2 \qquad (1)$$

and to receive the packet,the receiver consumes,

$$E_{rx} = K \cdot E_{elec} \qquad (2)$$

where E_{elec} represents the energy per bit that is necessary for digital processing, modulation, and ϵ_{fs} represents the energy per bit dissipated in the amplifier for the free space distance d transmission [10]. While for the cluster head nodes, they need to compress the data from the corresponding cluster member nodes and relay such data to the base station or satellite. The corresponding dissipating energy is,

$$E_{ch} = K \cdot M \cdot E_{elec} + K \cdot M \cdot E_{DS} + K \cdot \epsilon_{mp} \cdot d^4 \qquad (3)$$

where E_{ch} represents the energy consumption of cluster head, E_{DS} represents the energy per bit that is necessary for digital processing and compression of the data collected by a node, and ϵ_{mp} represents the energy dissipated in the amplifier for the multi-path distance transmission [10]. M is the number of nodes in a cluster.

III. ACCESS-BASED ENERGY EFFICIENT PROTOCOL ARCHITECTURE

We propose Access-Based Energy Efficient Clustering Protocol (ABEE). With the stochastic contention resolution scheme, ABEE is a request-response message broadcast protocol with first-come-first-serve selection. ABEE has corresponding message formats, and regulates a systematic logic for the nodes to act when a message arrives. The protocol also specifies a hand over scheme for the cluster head to pass its authority to one of its member nodes, in order to minimize the energy dissipation during the data transmission. To optimize this protocol design, we proposed the Mass Center Merge Algorithm and the Distance Merge Algorithm for Rational Distribution.

A. Mass Center Merge Algorithm

Because of the high density of the sensor nodes distribution in a large scale network, there is a relatively high correlation between the adjacent nodes, even within a same cluster. The highly correlated information data that collected by each node is the premise for the cluster head to preprocess and compress the raw data then relay them to the high-level hierarchy, such as base station or satellite. Because all the member nodes are within one hop away from their corresponding cluster head, with several tens of nodes in certain mobility, an accidentally"dead" (running out of power) node is not fatal to the whole cluster, if it is not the cluster head. Also because of the mobility of the nodes, some adjacent nodes may move into the zone used to belong to the"dead" node to replenish. Therefore, it is more rational to focus in the whole cluster as an entity. Our goal is to let the nodes in the certain cluster to be cluster head in turns, based on certain criterion that the

total energy depletion is minimized. We assume the energy dissipation for a member node in a specific cluster during a certain data transmission round is,

$$\Delta E_i = K \cdot E_{elec} + K \cdot \epsilon_{fs} \cdot d_i^2 \quad (4)$$

and the total energy dissipation of a cluster during one data transmission round is,

$$\Delta E_{total} = E_{ch} + \sum_{i=1}^{M-1} \Delta E_i \quad (5)$$

During the transmission, the payload data packet length and the corresponding data compression energy dissipation for a certain number of nodes are fixed, then the energy dissipation should be

$$\Delta E_{total} = E_{ch} + (M-1) \cdot K \cdot E_{elec} + K \cdot \epsilon_{fs} \cdot \sum_{i=1}^{M-1} d_i^2 \quad (6)$$

The most direct factor that the clustering protocol can affect energy is the distance between the nodes to the cluster head. The less the distance is, the more energy can be saved during the data transmission. In order to minimize the total energy depletion, we try to minimize the second term of (5). Here we suppose the coordinate of the node i is (x_i, y_i). The Euclidean distance from each node to the ideal cluster head position is,

$$d_i = \sqrt{(x_i - x_{ideal})^2 + (y_i - y_{ideal})^2} \quad (7)$$

where x_{ideal} and y_{ideal} represent the coordinate of the optimal position where the ideal cluster head locates. Minimizing the summation of the distance $\sum_{i=1}^{M-1} d_i^2$, we can get the smallest value of ΔE_{total} to minimize the energy dissipation each round. Here, we treat the whole cluster as an entity and each node stands for a particle with equal mass to form the entity. Based on the geometry knowledge, the ideal cluster head position is the mass center of the cluster. After the cluster head collects all the coordinate information of the member nodes, based on this selection criterion, it can select the cluster head candidate for the next turn, which is the closest to the mass center. Then pass its cluster head authority to the candidate. If itself is the closest to the mass center, it remains to be the cluster head.

B. Distance Merge Algorithm for Rational Distribution

The distribution of the network that is controlled by the self-organized protocol is not likely to be very uniform and rational. Some nodes might be locally huddled, while some might be isolated. We design a merge algorithm to uniform the clusters distribution. Each cluster head tries to listen the timely $HELLO$ message from other cluster heads. Based on the coordinate information provided by the nodes that send the $HELLO$ message , the cluster head can calculate the distance from itself and the other cluster head. If such distance is below a certain threshold, these two clusters will merge into one cluster. Likewise, if the member node receives a $HELLO$ message from a more closer cluster head, it will try to leave the present cluster and join the closer cluster head. The simulation result shows that such algorithm can improve the rationality

of the clusters distribution while retaining the convenience of self-organization.

C. Protocol Description

Fig.1 shows the message packet format of the ABEE. We assume that when a node becomes active, it begins as an idle node, and can get its present position information (it can be realized by the GPS system). Fig.2 shows the state diagram for the ABEE. Each node is assumed to have a unique ID in the sensor network.

Destination ID (8 bits)	Source ID (8 bits)	Message (8 bits)	Status (8 bits)	My_X_position (8 bits)	MY_Y_position (8 bits)

Fig. 1. The control packet structure of ABEE

Because the ordinary nodes can either be member nodes or cluster head nodes, ABEE is divided into three cases. All nodes start as idle node case. In the idle state, the node is to broadcast a REQ_TO_JOIN message and send the $TIME\_OUT\_1$ and wait for the response from the neighbor cluster heads. If this node receives $HELLO$ messages from some cluster head, it will pick up the first received (that is why we call it access-based), and reply to the corresponding cluster head a $JOIN$ message to make a notice. However, if when the $TIMEUP\_1$ expires, the node has not received the $HELLO$ message, the node will broadcast $HELLO$ message to become a cluster head.

After the idle nodes send $JOIN$ and receive the corresponding ACK message from the cluster head that it wants to join, the node will become a member node. In the member node state, the node will keep sending $HEART\_BEAT$ message to inform the cluster head its present position. Also, the member node listen the $HELLO$ message from its cluster head as "heart beat" signal and update the corresponding status list in its memory. Because all the nodes in the whole network are using the same control channel, the member nodes can also receive the $HELLO$ message from the other adjacent cluster heads. Based on the position information contained in the packet, it can calculate the distances from such cluster heads. After comparison with the distance from its present cluster head, the member node will choose a closer cluster head to join and send $DISCONNECT$ message to the present cluster head. There is a certain threshold distance d_{th} to prevent the frequently cluster switching, which means that the distance to the future cluster head should be at least d_{th} shorter than the distance to present cluster head. If after the $WAIT\_HELLO\_TIME\_OUT$, the node has not received the $HELLO$ message from the cluster head, it will assume the cluster head abnormally turns off and it will switch back to the idle state to find a new cluster to join.

In the cluster head case, the cluster head is responsible to maintain the structure of the cluster. It will send the $HELLO$ message after every certain time interval of $SEND\_HELLO\_TIME$ to inform the surrounding nodes its current position, which also can be treated as a "heart beat" signal of the cluster head. If $JOIN$ message is received,
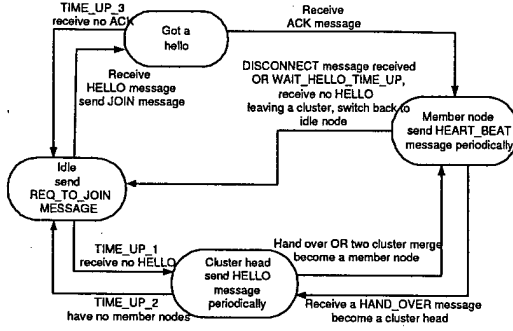
3

Fig. 2. The state transition of a node in ABEE

the cluster head will send out the *ACK* message to confirm the node to join the cluster. If the cluster head received a *HELLO* message from a distance that is shorter than d_{ch}, which means distance of two cluster head is below a certain threshold d_{ch}, the cluster head will broadcast a *MERGE* notice to it members and the cluster will merge into the other cluster. Whenever a node enters the cluster head state, it will set up the following timers and reset them again after they expire.

1) *TIME_OUT_2*. After this time out, if the cluster head has not received the *HEART_BEAT* signal from a member node, it assumes the member node has been abnormally shut down or out of cluster range, and will delete it from the status list in the memory. Also the node will check the number of member nodes it still has. If there is no member node in the list, which means it is a cluster head without any member node, it will switch back to the idle state and try to join another cluster head.

2) *HAND_OVER_TIME*. After this time out, the cluster head will calculate the position of the mass center of the cluster, based on the coordinates information of all the nodes in the cluster, which is stored in its memory and updated by every *HEART_BEAT* message from its members. Then it will select the node that is closest to the mass center position and pass its cluster head authority to it. If the candidate node is itself, it remains to be the cluster head.

D. Abnormal Conditions

In order to minimize the impact of the abnormal conditions, such as sudden node failure, channel error or erasure (Because we use the CSMA/CA scheme in the MAC layer), we have designed the aforementioned time-out schemes to prevent"dull" nodes in the status list. Sometimes the abnormal conditions might cause the message loss. However, since the *REQ_TO_JOIN*, *HELLO*, and *DISCONNECT* messages are not targeted for any specific nodes, such message lost will not ruin the structure of the cluster, but only slow down the speed of convergence. We also have designed the confirmation acknowledgement message *ACK* to ensure the idle nodes to join a new cluster.

IV. SIMULATIONS

We performed computer simulations using OPNET Modeler. We build up a generic sensor node model that can randomly move in a specific scenario and use a public channel to communicate the protocol control message. All nodes use CSMA/CA scheme to access the public channel and can be either cluster head or cluster member. In the simulations, 100 nodes are randomly deployed within a region of $400m \times 400m$. The initial energy that is stored in each node is equal. We assume each node has infinite data information to send and the data rate is 500 bytes per second. The parameters for the energy dissipation are as follows, $E_{elec} = 50nJ/bit$, $\epsilon_{fs} = 10pJ/bit/m^2$, $\epsilon_{mp} = 0.0013pJ/bit/m^4$, $E_{DS} = 5pJ/bit/signal$ [13]. In order to focus on the impact that the network topology brings to the energy dissipation and performance of the sensor nodes, we do not account for the energy requirements or delay for the network information updates and topology maintenance in our simulations. The mobility model is with memory characteristic called a one-step Markov path model [14]. In the Markov path model, a node has a higher probability of moving in the same direction as the previous move. Fig.3 shows the probability assignment in six different directions used in our simulation. The ground speed of each nodes is $3m/s$. The transmission range of each node is $200m$. All the nodes will randomly turn on within $5s$ after the simulations begin. The information detection range for each node is relative to the remaining energy of the node, which satisfy the free space path loss model as the following equation,

$$D_{detect} = \sqrt{E_{node} \times p} \qquad (8)$$

We assume the maximum detection range for a sensor node is $10m$ if the node energy storage E_{node} is more than $5J$. Whenever the energy storage is lower than $5J$, the detection range will decrease as the energy dissipation according to (8), in which the coefficient $p = 0.05m^2/J$.
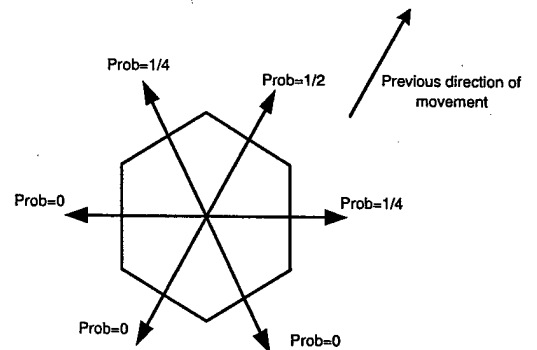

Fig. 3. One-step Markov path model with memory characteristic

A. Cluster structure

This section shows the cluster topology maintenance performance of the ABEE in comparison with the clustering

4

strategy ABCP proposed in [11]. We observed the impact of the distance merge algorithm on the cluster structure. For ABEE, two cluster heads (which should be the nearest node to the mass center of the cluster based on the Mass Center Merge Algorithm) that are closer than a threshold distance d_{th} will merge into one cluster to prevent clusters over huddled. However, for ABCP, there is no such function except letting the single cluster head merge into another neighbor cluster. In these simulations, we assume the energy of each node is infinite, which can show how the clustering protocol impacts the topology. Fig.4 shows the evaluation of cluster number of the simulations. It can be seen that with the distance merge algorithm, the number of clusters with ABEE converges to be around 15, while the number of clusters with ABCP converges around 17.
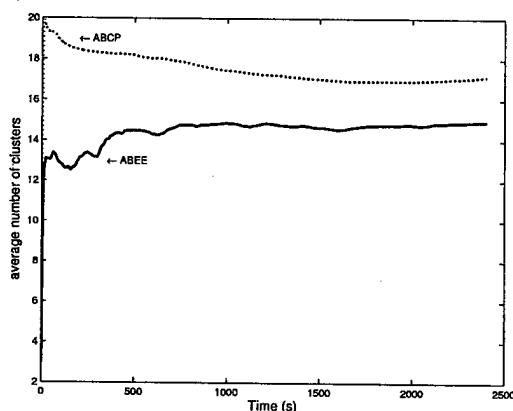

Fig. 4. Evaluation of cluster number

Because the distance merge algorithm combines some clusters into one, which are too close to each other, the distribution of the clusters will tend to be more rational. Less clusters means less overhead in coummunications and corresponding control meassage collisions. As in (3), because a large portion of energy is dissipated during the communication betweeen the cluster head and the base station, less cluster head means more energy will be saved during the uplink transmission. Given the energy store limit, the benefit of rational cluster topology will be discussed in the next section.

B. System lifetime

Since the high correlation among the detected information in the sensor nodes, we can make data compression in the cluster head node to save the communication bandwidth in the uplink channel from the cluster head to the base station. In these simulations, we assume the initial energy storage of each node is equal to $5J$ and the location of the base station is at $(0,0)$. All the nodes are randomly scattered within an initial $400m \times 400m$ area, whose top left corner locates at $(250,250)$. All nodes follow the aforementioned mobility model. We assume each node has infinite data, which are collected within the detection range, to send to the base station. If the node's energy storage is below zero, we treat

it as a "dead" node that can no longer collect or transmit information. To the whole system, we recorded the remaining active nodes number as the index of the network lifetime. The more nodes survive after a certain time, the longer the lifetime of the network. Fig.5 shows the comparison of the number of remaining active nodes of the ABEE and ABCP protocol. Obviously the ABEE protocol prolongs the system lifetime. It takes around $130s$ in the ABCP scenario for the number of remaining active nodes to reduce to 50, from initial 100 nodes, while ABEE protocol prolong this time to $250s$. There is a 92.3% lifetime enhancement we can get from the ABEE protocol. For these simulations, energy is consumed whenever a node transmits or receives data or performs data aggregation. The results here do not account for the potential energy dissipation of the clustering procedure. Another crucial and application-independent criterion to the network quality is the amount of data received at the base station. The more data the base station receives, the more accurate the image of the surveillance will be got. Fig.6 shows the number of data signals received at the base station over time. It is obvious that the ABEE protocol can make the network send more data to the base station than the ABCP protocol, given the same amount of energy within the same period.
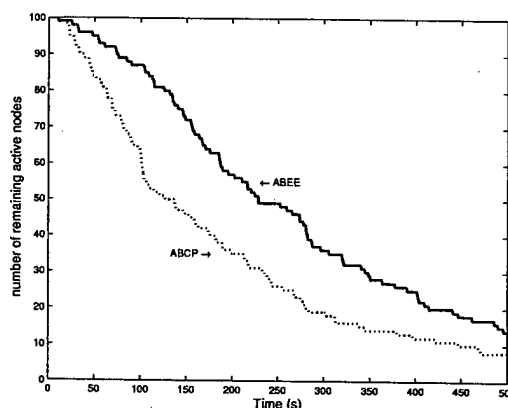

Fig. 5. Evaluation of remaining active nodes

C. Network Coverage

With the same amount of energy stored in the each node, besides the number of remaining nodes in the surveillance area as time elapses, we can also evaluate a network by the coverage. Because of the high correlation among the data collected by the sensor nodes, it is more important to sustain the network longer to collect more detailed data. We propose to record the ratio that the total effectively covered area by the active sensor nodes detection region to the total target area. Here we must deduct the overlaid area of two adjacent nodes. The higher this ratio, the more thoroughly the sensor network can cover the whole target area. In the simulation, we just focus into the $400m \times 400m$ target area. It may be possible that some nodes move out of the region and cover some useless area. In the simulations, we just consider all the
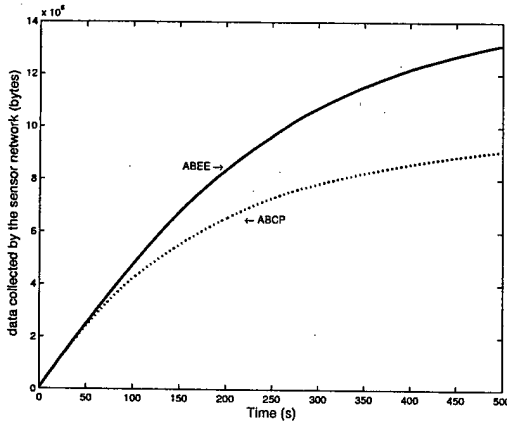
5

Fig. 6.   Data received by the base station

order to construct a rational, energy efficient structure for the upper-level, ABEE contains a cluster-merge algorithm based on the mass-center estimation of each cluster. In contrast, the prior work focuses on the algorithm regarding for the rapidly deploy and stable network management, nevertheless lacking overall energy efficient consideration. In ABEE, with considering the major path-loss factor during the information data transmission, we try to minimize the energy dissipation of the whole cluster during each round of data transmission by introducing a hand over algorithm among the nodes. Simulations provide complete comparisons on cluster numbers, network lifetime and coverage of the network. As observed from the simulations, ABEE provides more rational clusters distribution to achieve low energy dissipation and better network coverage, which can dramatically improve performance of the wireless sensor network.

effectively covered area within the target area. Fig.7 shows the effectively covered area percentage. The theoretically perfect coverage (without any overlaid area of adjacent nodes) can easily calculated by,

$$(\pi \times D^2_{detect} \times N)/(400 \times 400) = 19.63\% \qquad (9)$$

where the $r = 10m$ is the detection radius of the nodes, which is change according to (8), and N is the total number of nodes, which is 100 in the simulations. It can be observed from the figure that the coverage starts from 14.38% and decreased continuously. It takes around $100s$ for the network of ABCP to reach 7% (half of the initial coverage), while $150s$ for the network of ABEE to reach the same level. There is around 50% gain in the lifetime of the network coverage.
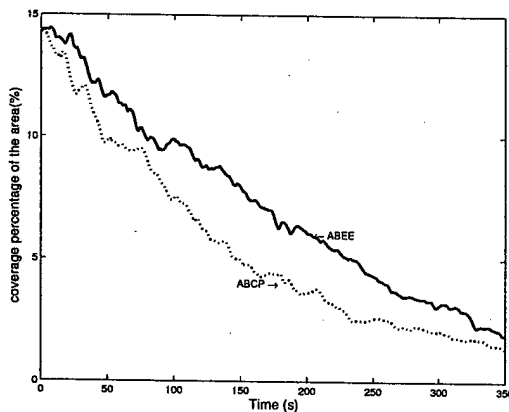

Fig. 7.   Effective coverage of the network

V. CONCLUSION

Considering the practical application affected by the deployment, energy constraints of the nodes and the high correlation among the data collected by the nodes, we propose the ABEE, a protocol that retains the advantage of access-based protocol, such as rapidly deployment, self-organization. In

REFERENCES

[1] C.R.Lin, M. Gerla, "Adaptive clustering for mobile wireless networks" *IEEE Journal on Selected Areas in Communications*, vol 15, no. 7 , Sept 1997, pp. 1265 -1275

[2] D. J. Baker, J. Wieselthier, A. Ephremides, "A distributed algorithm for scheduling the activation of links in a self-organizing, mobile, radio netwrok" *Proc. IEEE Int. Conf. Communications*, pp.1F.6.1-2F.6.4 June 1982

[3] D. J. Baker, "Distributed control of broadcast radio networks with changing topologies" *Proc. IEEE Infocom, San Diego, CA,*, pp.49-55, Apr 1983

[4] T. Kwon, M. Gerla, "Clustering with power contol" *Proc. MILCOM ,* vol 2, Atlantic City, NJ, Nov.1999

[5] L. Clare, G. Pottie, J. Agre, "Self-organizing distributed sensor networks" *Proc. SPIE Conf. Unattended Ground Sensor Technologies and Applications,* vol 3713, Orlando, FL, Apr 1999, pp.229-237

[6] A. B. McDonald, T. F. Znati, "A mobility-based framework for adaptive clustering in wireless ad hoc networks" *IEEE Journal on Selected Areas in Communications,* vol 17, no. 8 , Aug. 1999 pp.1466 -1487

[7] Z. J, Haas, B. Liang, "Ad hoc mobility management with uniform quorum systems" *IEEE/ACM Transactions on Networking,* vol 7, no.2 , April 1999 pp. 228 -240

[8] W. Chen, N. Jain, S. Singh, "ANMP: ad hoc network management protocol" *IEEE Journal on Selected Areas in Communications,* vol 17, no.8 , Aug 1999, pp. 1506 -1531

[9] A. Iwata, Ching-Chuan Chiang, Guangyu Pei, M. Gerla, Tsu-Wei Chen, "Scalable routing strategies for ad hoc wireless networks" *IEEE Journal on Selected Areas in Communications,* vol 17, no.8 , Aug 1999, pp. 1369 -1379

[10] W. B. Heinzelman, A. P. Chandrakasan, H. Balakrishnan, "An application-specific protocol architecture for wireless microsensor networks" *IEEE Transactions on Wireless Communications,* vol 1, no. 4 , Oct. 2002, pp. 660 -670

[11] T.C. Hou, T.J. Tsai, "A access-based clustering protocol for multihop wireless ad hoc networks" *IEEE Journal on Selected Areas in Communications,* vol 19, no. 7 , July 2001, pp. 1201 -1210

[12] T. Rappaport, "Wireless Communications: Principles and Practice" Englewood Cliffs, NJ: Prentice-Hall, 1996

[13] A. Wang, W. R Heinzelman; A. P Chandrakasan, "Energy-scalable protocols for battery-operated microsensor networks" *IEEE Workshop on Signal Processing Systems,* 1999. SiPS 99. 20-22 Oct. 1999, pp. 483 -492

[14] T. C. Hou, T. J. Tsai, "Adaptive clustering in a hierarchical ad hoc network" *Proc. Int. Computer Symp.,Tainan, Taiwan,R.O.C.,* Dec.1998, pp.171-176.

6

Clusterhead Election for Mobile Ad Hoc Wireless Network

Qilian Liang
Department of Electrical Engineering
University of Texas at Arlington
Arlington, TX 76019-0016 USA
E-mail: liang@uta.edu

Abstract— Selecting an appropriate clusterhead can save power for the whole ad hoc wireless network. Generally, clusterhead election for mobile ad hoc network is based on the distance to the centroid of a cluster, and the closest one is elected as the clusterhead; or pick a node with the maximum battery capacity as the clusterhead. In this paper, we present a clusterhead election scheme using fuzzy logic system (FLS) for mobile ad hoc wireless networks. Three descriptors are used: distance of a node to the cluster centroid, its remaining battery capacity, and and its degree of mobility. The linguistic knowledge of clusterhead election based on these three descriptors is obtained from a group of network experts. 27 FLS rules are set up based on the linguistic knowledge. The output of the FLS provides a clusterhead possibility, and node with the highest possibility is elected as the clusterhead.

Key Words : Clusterhead election, ad hoc networks, mobility, fuzzy logic system, decision making.

I. INTRODUCTION

Ad hoc networks (AHN) are self-organizing entities that are deployed on demand in support of various activities including collaborative computing, multimedia classroom, disaster relief, search and rescue, and interactive mission planning. It is important to have a power control and management scheme for Ad Hoc wireless networks to maximally conserve battery power, because battery life is not expected to increase significantly in the coming years. Rodoplu and Meng [15] developed a general mathematical theory for designing a minimum power topology within one cluster for a stationary Ad Hoc network. In [16], Wu *et al* combined the concept of power control and with the busy-tone-based protocols to further increase channel utilization. Similar to [16], a power control loop was proposed [1] to control the transmitting and receiving power level in ad-hoc wireless network. In [17], a location-aided power aware routing protocol was proposed. In [5], a power-efficient gathering in sensor information systems (PEGASIS) method is proposed, but no mobility of sensor nodes is assumed. Singh et al [13] proposed power-aware routing and discussed different metrics in power-aware routing; Li et al [4] extended their work and proposed an online power aware routing in wireless ad-hoc networks. In [12], a power aware virtual base station (PA-VBS) protocol was proposed, which elects a mobile node from a set of nominees to act as a base station. In [14], a new power aware routing protocol was proposed to evenly distribute the power consumption rate of each node and minimize the overall transmission power for each connection request simultaneously. In this paper, we propose a clusterhead election scheme for mobile ad hoc wireless networks considering power management and saving. We believe that selecting a good clusterhead can save power for the whole ad hoc network.

Generally, a node with the maximum battery capacity or a node with the nearest distance to the cluster centroid is elected as the clusterhead. In this paper, we propose a scheme which makes clusterhead selection decision based on the following three descriptors:

1. distance of a node to the cluster centroid,
2. its remaining battery capacity, and
3. its degree of mobility.

Several special issues on intelligent techniques in high speed networks have been published by *IEEE Journal on Selected Areas in Communications* (e.g. [3] [2]), which shows that intelligent techniques have been extensively applied to high speed networks. According to [2], "The advantages of intelligent techniques are numerous, most notably are learning from experience, ...". In this paper, we apply fuzzy logic systems (FLSs) to clusterhead election for ad hoc wireless networks. FLSs are known to represent and numerically manipulate linguistic rules in a natural way and for their ability to handle problems that conventional control theory cannot approach successfully because the latter relies on a valid and accurate model which does not always exist. We consider the design of a FLS that is based on rules collected by surveying a group of experts rather than a single expert, and design a FLS based on the experiences from these experts.

In Section II, we briefly introduce the fuzzy logic system. In Section III, we design the rules for clusterhead election based on the experiences from a group of network experts. In Section IV, we present the computation of the rule-based FLS and generate the decision surface for clusterhead election, and compare our scheme against the nearest distance and maximum battery capacity methods based on one example. Conclusions are presented in Section V.

II. Overview of Fuzzy Logic Systems

Figure 1 shows the structure of a fuzzy logic system (FLS) [9]. When an input is applied to a FLS, the inference engine computes the output set corresponding to each rule. The defuzzifer then computes a crisp output from these rule output sets. Consider a p-input 1-output FLS, using singleton fuzzification, *center-of-sets* defuzzification [11] and "IF-THEN" rules of the form [7]

$$R^l : \text{IF } x_1 \text{ is F}_1^l \text{ and } x_2 \text{ is F}_2^l \text{ and } \cdots \text{ and } x_p \text{ is F}_p^l,$$
$$\text{THEN } y \text{ is G}^l.$$

Assuming singleton fuzzification, when an input $\mathbf{x}' = \{x_1', \ldots, x_p'\}$ is applied, the degree of firing corresponding to the lth rule is computed as

$$\mu_{\text{F}_1^l}(x_1') \star \mu_{\text{F}_2^l}(x_2') \star \cdots \star \mu_{\text{F}_p^l}(x_p') = \mathcal{T}_{i=1}^p \mu_{\text{F}_i^l}(x_i') \quad (1)$$

where $\star$ and $\mathcal{T}$ both indicate the chosen t-norm. There are many kinds of defuzzifiers. In this paper, we focus, for illustrative purposes, on the center-of-sets defuzzifier [11]. It computes a crisp output for the FLS by first computing the centroid, c_{G^l}, of every consequent set G^l, and, then computing a weighted average of these centroids. The weight corresponding to the lth rule consequent centroid is the degree of firing associated with the lth rule, $\mathcal{T}_{i=1}^p \mu_{\text{F}_i^l}(x_i')$, so that

$$y_{cos}(\mathbf{x}') = \frac{\sum_{l=1}^M c_{\text{G}^l} \mathcal{T}_{i=1}^p \mu_{\text{F}_i^l}(x_i')}{\sum_{l=1}^M \mathcal{T}_{i=1}^p \mu_{\text{F}_i^l}(x_i')} \quad (2)$$

where M is the number of rules in the FLS.

In this paper, we design a FLS for clusterhead election. The rules are designed based on the knowledge from a group of network experts.

III. Extracting the Knowledge for Clusterhead Election

We collect the knowledge for clusterhead election based on the following three descriptors:
1. distance of a node to the cluster centroid,
2. its remaining battery capacity, and
3. its degree of mobility.

The linguistic variables used to represent the distance of a node to the cluster centroid were divided into three levels: *near*, *moderate*, and *far*; and those to represent its remaining battery capacity and degree of mobility were divided into three levels: *low*, *moderate*, and *high*. The consequent – the possibility that this node will be elected as a clusterhead – was divided into 5 levels, *Very Strong, Strong, Medium, Weak, Very Weak*.

We designed questions such as:

IF *distance of a node to the cluster centroid* is *near*, and *its remaining battery capacity* is *low*, and *its degree of mobility* is *moderate*, THEN the possibility that this node will be elected as a clusterhead is

_____.

so we need to set up $3^3 = 27$ (because every antecedent has 3 fuzzy sub-sets, and there are 3 antecedents) rules for this FLS.

As pointed out in [10], "words mean different things to different people", and in [8], "the decision makers may have the same preferences to a particular alternative, e.g., highly preferred but with different degrees;" so, we created one survey for the network experts. We used rules obtained from the knowledge of 6 network experts. These experts were requested to choose a consequent using one of the five linguistic variables. Different experts gave different answers to the questions in the survey. Table I summarizes the questions used in this survey, and Table II captures the results from the completed survey.

We used trapezoidal membership functions (MFs) to represent *near, low, far*, and *high*, and triangle MFs to represent *moderate*. We show these MFs in Fig. 2a.

IV. Knowledge Processing and Clusterhead Election Decision

In our approach to forming a rule base, we chose a single consequent for each rule. To do this, we averaged the centroids of all the responses for each rule and used this average in place of the rule consequent centroid. Doing this leads to rules that have the following form:

R^l : IF *distance of a node to the cluster centroid* (x_1) is F_l^1, and *its remaining battery capacity* (x_2) is F_l^2, and *its degree of mobility* (x_3) is F_l^3, THEN the possibility that this node will be elected as a clusterhead (y) is c_{avg}^l.

where $l = 1, \ldots, 27$. c_{avg}^l is defined as

$$c_{avg}^l = \frac{\sum_{i=1}^5 w_i^l c^i}{\sum_{i=1}^5 w_i^l} \quad (3)$$

in which w_i^l is the number of people choosing linguistic label i for the consequent of rule l ($i = 1, \cdots, 5; l = 1, \ldots, 27$) (see Table II); and, c^i is the centroid of the ith consequent set ($i = 1, 2, \cdots, 5$). The centroids of the three fuzzy sets depicted in Fig. 2b are $c^1 = 1.0561$, $c^2 = 3$, $c^3 = 5$, $c^4 = 7$, and $c^5 = 8.9439$.

To illustrate the use of (3), note, for example, that

$$c_{avg}^{11} = \frac{3c^1 + 2c^2 + c^3}{3 + 2 + 1} = 2.3614 \quad (4)$$

All 27 c_{avg}^l values are listed in Table II.

For every input (x_1, x_2, x_3), the output is computed using

$$y(x_1, x_2, x_3) = \frac{\sum_{l=1}^{27} \mu_{F_l^1}(x_1) \mu_{F_l^2}(x_2) \mu_{F_l^3}(x_3) c_{avg}^l}{\sum_{l=1}^{27} \mu_{F_l^1}(x_1) \mu_{F_l^2}(x_2) \mu_{F_l^3}(x_3)} \quad (5)$$

By repeating these calculations for $\forall x_i \in [0, 10]$, we obtain a hypersurface $y(x_1, x_2, x_3)$. Since it's a 4-D surface (x_1, x_2, x_3, y), it's impossible to be plot visually.

If we have $x_1 = 1$, and two other antecedents, *its remaining battery capacity* (x_2) and *its degree of mobility* (x_3) are variables, for every input $(1, x_2, x_3)$, the output is computed using

$$y(1, x_2, x_3) = \frac{\sum_{l=1}^{27} \mu_{F_l^1}(1) \mu_{F_l^2}(x_2) \mu_{F_l^3}(x_3) c_{avg}^l}{\sum_{l=1}^{27} \mu_{F_l^1}(1) \mu_{F_l^2}(x_2) \mu_{F_l^3}(x_3)} \quad (6)$$

By repeating these calculations for $\forall x_2 \in [0, 10]$ and $\forall x_3 \in [0, 10]$, we obtain a hypersurface $y(1, x_2, x_3)$, as plotted in Fig. 3(a). In contrast, if we have $x_1 = 9$, and two other antecedents, *its remaining battery capacity* (x_2) and *its degree of mobility* (x_3) are variables, similarly we obtain another surface $y(9, x_2, x_3)$, as plotted in Fig. 3(b). From Fig. 3ab, we see that although a node is very close to the cluster centroid $(x_1 = 1)$, its possiblity to be chosen as clusterhead can be lower than some node far from the centroid $(x_1 = 9)$.

As an example, we randomly generated 100 nodes (a cluster) within a square with 100 meters on each side. Each node has random battery capacity in [0, 10], and random mobility degree in [0, 10]. The distances of each node to the cluster centroid are normalized to [0, 10] scale. Each node is characterized by the three descriptors. We apply (5) to compute the election possibility for each node, and pick the node having the highest election possibility as the clusterhead, as illustrated in Fig. 4. We also plotted the node having the maximum battery capacity and the node having the nearest distance to the cluster centroid in Fig. 4.

V. CONCLUSIONS

Generally, clusterhead election for mobile ad hoc network is based on the distance to the centroid of a cluster, and the closest one is elected as the clusterhead. We present a clusterhead election scheme using fuzzy logic system (FLS) for mobile ad hoc wireless networks. Three descriptors are used: distance of a node to the cluster centroid, its remaining battery capacity, and and its degree of mobility. The linguistic knowledge of clusterhead election based on these three descriptors is obtained from a group of network experts. 27 FLS rules are set up based on the linguistic knowledge. The output of the FLS provides a clusterhead possibility, and node with the highest possibility is elected as the

clusterhead. Other appropriate rules can be created that optimize routing efficiency (e.g., number of hops, QoS, etc).

VI. ACKNOWLEDGEMENT

REFERENCES

[1] S. Agarwal, et al, "Distributed power control in ad hoc wireless networks," *IEEE 12th International Symposium on Personal Indoor Mobile Radio Communications (PIMRC)*, San Diego, CA, Sept 2001.

[2] E. Gelenbe, I. W. Habib, S. Palazzo, and S. Douligeris, eds, Special Issue on Intelligent Techniques in High Speed Networks, *IEEE J. Selected Areas in Communications*, vol. 18, no. 2, Feb 2000.

[3] I. W. Habib, R. Morris, H. Saito, and B. Pehrson, eds, Special Issue on Computational and Artificial Intelligence in High Speed Networks, *IEEE J. Selected Areas in Communications*, vol. 15, no. 2, Feb 1997.

[4] Q. Li, J. Aslam, and D. Rus, "Online power-aware routing in wireless ad-hoc networks," *Proc. of Annual ACM/IEEE International Conf. on Mobile Computing and Networking (MobiCom)*, Rome, Italy, pp. 97-107, 2001.

[5] S. Lindsey, and C. S. Raghavendra, "PEGASIS: power-efficient gathering in sensor information systems," to be presented at *IEEE Aerospace Conference*, March 2002.

[6] S. Lindsey, K. Sivalingam, C. S. Raghavendra, "Power Optimization in Routing Protocols for Wireless and Mobile Networks," *Handbook of Wireless Networks and Mobile Computing*, Ed. Ivan Stojmenovic, John Wiley and Sons, 2001.

[7] E. H. Mamdani, " Applications of fuzzy logic to approximate reasoning using linguistic systems", *IEEE Trans. on Systems, Man, and Cybernetics*, vol. 26, no. 12, pp. 1182-1191, 1977.

[8] Marimin, M. Umano, I. Hatono, and H. Tamura, " Linguistic labels for expressing fuzzy preference relations in fuzzy group decision making," *IEEE Trans. Systems, Man, Cybernetics–Part B: Cybernetics*, vol. 28, no. 2, pp. 205-218, April 1998.

[9] J. M. Mendel, "Fuzzy Logic Systems for Engineering : A Tutorial," *Proceedings of the IEEE*, vol. 83, no. 3, pp. 345-377, March 1995.

[10] J. M. Mendel, "Computing with words when words can mean different things to different people," *Int'l. ICSC Congress on Computational Intelligence: Methods & Applications, Third Annual Symposium on Fuzzy Logic and Applications*, Rochester, NY, June 22-25, 1999.

[11] J. M. Mendel, *Uncertain Rule-Based Fuzzy Logic Systems*, Prentice-Hall, Upper Saddle River, NJ, 2001.

[12] A. Safwat, H. Hassanein, and H. Mouftah, "Power-aware fair infrastructure formation for wireless mobile ad hoc communications," *Proc. of Globecom'2001*, pp. 2832-2836, San Antonio, TX, Sept 2001.

[13] S. Singh, M. Woo, and C. S. Raghavendra, "Power-aware routing in mobile ad hoc networks," *Proc. of Annual ACM/IEEE International Conf. on Mobile Computing and Networking (MobiCom)*, Dallas, TX, pp. 181-190, 1998.

[14] C.-K. Toh, "Maximum battery life routing to support ubiquitous mobile computing in wireless ad hoc networks," *IEEE Communications Magazine*, vol. 39, no. 6, pp. 138-147, July 2000.

[15] V. Rodoplu, and T. Meng, " Minimum energy mobile wireless networks," *IEEE J. Selected Areas in Communications*, vol. 17, no. 8, pp. 1333-1344, Aug 2000.

[16] S.-L. Wu, Y.-C. Tseng, and J.-P. Sheu, "Intelligent medium access for mobile ad hoc networks with busy tones and power control," *IEEE J. Selected Areas in Communications*, vol. 18, no. 9, pp. 1647-1657, Sept 2000.

[17] Y. Xue and B. Li, "A location-aided power-aware routing protocol in mobile ad hoc networks," *Proc. of Globecom'2001*, pp. 2837-2841, San Antonio, TX, Sept 2001.
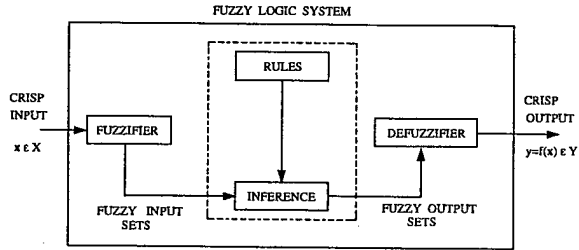
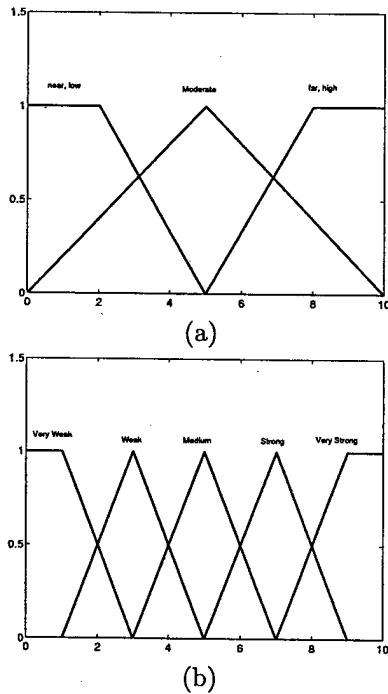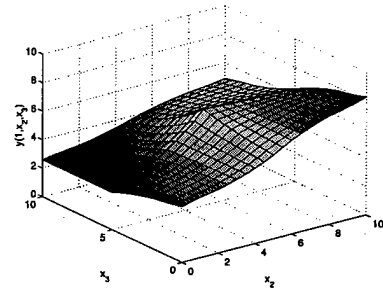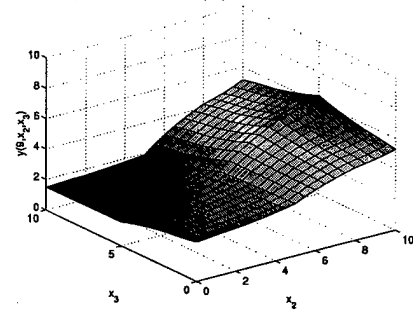Fig. 1. The structure of a fuzzy logic system.

(a)

(b)

Fig. 2. The MFs used to represent the linguistic labels. (a) MFs for antecedents, and (b) MFs for consequent.

(a)

(b)

Fig. 3. The clusterhead election decision surface for fixed distance to the centroid (x_1), (a) when $x_1 = 1$, and (b) when $x_1 = 9$.
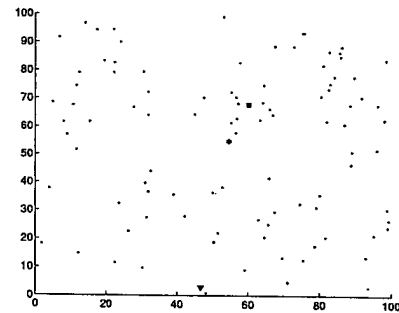
Fig. 4. One example for clusterhead election. The elected clusterhead (distance: 2.2403, battery capacity: 8.4276, and mobility degree 0.8839) is denoted using 'square' □, the node with maximum battery capacity (distance: 7.9852, battery capacity: 9.8141, and mobility degree 1.2977) is denoted using 'triangle (down)' ∇, and the node with nearest distance (distance: 0.2307, battery capacity: 3.2909, and mobility degree 7.6049) to the centroid is denoted using 'hexagram' ⋆.

4

TABLE I

THE QUESTIONS FOR CLUSTERHEAD ELECTION FOR MOBILE AD HOC WIRELESS NETWORK. ANTECEDENT 1 IS *distance of a node to the cluster centroid*, ANTECEDENT 2 IS *its remaining battery capacity*, ANTECEDENT 3 IS *its degree of mobility*, AND CONSEQUENT IS *the possibility that this node will be elected as a clusterhead.* THE EXPERTS WERE ASKED TO FILL IN THE BLANK FOR THE CONSEQUENT USING ONE OF FIVE LINGUISTIC LABELS (VERY WEAK, WEAK, MEDIUM, STRONG, VERY STRONG).

Question #	Antecedent 1	Antecedent 2	Antecedent 3	Consequent
1	near	low	low	
2	near	low	moderate	
3	near	low	high	
4	near	moderate	low	
5	near	moderate	moderate	
6	near	moderate	high	
7	near	high	low	
8	near	high	moderate	
9	near	high	high	
10	moderate	low	low	
11	moderate	low	moderate	
12	moderate	low	high	
13	moderate	moderate	low	
14	moderate	moderate	moderate	
15	moderate	moderate	high	
16	moderate	high	low	
17	moderate	high	moderate	
18	moderate	high	high	
19	far	low	low	
20	far	low	moderate	
21	far	low	high	
22	far	moderate	low	
23	far	moderate	moderate	
24	far	moderate	high	
25	far	high	low	
26	far	high	moderate	
27	far	high	high	

TABLE II

HISTOGRAMS OF EXPERT RESPONSES ABOUT CLUSTERHEAD ELECTION FOR MOBILE AD HOC WIRELESS NETWORK. 6 NETWORK EXPERTS ANSWERED THE QUESTIONS. THE ENTRIES IN THE SECOND − SIXTH COLUMNS CORRESPOND TO THE WEIGHTS w_1^l, w_2^l, w_3^l, w_4^l, AND w_5^l, RESPECTIVELY.

Rule Number (l)	very weak	weak	medium	strong	very strong	c_{avg}^l
1	0	3	3	0	0	4.0
2	1	5	0	0	0	2.676
3	3	1	2	0	0	2.6947
4	0	0	3	3	0	6.0
5	0	0	0	5	1	7.3240
6	0	4	1	1	0	4.0
7	0	0	0	1	5	8.6199
8	0	0	1	5	0	6.6667
9	0	1	4	1	0	5.0
10	0	4	2	0	0	3.6667
11	3	2	1	0	0	2.3614
12	4	1	1	0	0	2.0374
13	0	1	3	2	0	5.3333
14	1	1	4	0	0	4.0093
15	2	3	0	1	0	3.0187
16	0	0	2	3	1	6.6573
17	0	1	2	3	0	5.6667
18	0	3	2	1	0	4.3333
19	2	4	0	0	0	2.3520
20	5	1	0	0	0	1.3801
21	5	1	0	0	0	1.3801
22	1	4	1	0	0	3.0093
23	1	4	1	0	0	3.0093
24	5	0	1	0	0	1.7134
25	0	2	2	2	0	5.0
26	0	0	2	3	1	6.6573
27	0	2	2	1	1	5.3240